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An Evaluation of Very Large Airplanes and Alternative Fuels

W. T. Mikolowsky and L. W. Noggle

with Contributions by W. F. Hederman and R. E. Horvath

A Project AIR FORCE report
prepared for the
United States Air Force

Rand
SANTA MONICA, CA. 90406

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Very large airplanes using alternative fuels are examined in the context of existing and possible future Air Force missions. Synthetic jet fuel (JP), liquid methane, liquid hydrogen, and nuclear propulsion are the fuel alternatives selected for detailed analysis. Conceptual designs of airplanes using each of these fuels were developed and estimates were made of their life-cycle cost and life-cycle energy consumption. Mission analyses were performed to determine the effectiveness of the alternative airplanes in strategic airlift specifically and in the station-keeping role in general. Results indicate that for most military applications airplanes with gross weights in excess of one million pounds promise to be superior to any contemporary airplanes in terms of cost-effectiveness and energy-hydrocarbon jet fuel, whether manufactured from oil shale, coal or crude oil, remains the most attractive aviation fuel for future Air Force use. Policy recommendations are made pertaining both to alternative fuels and to advanced-technology large airplanes. Future research and development requirements are also identified.(see also R-1829-PR). Ref. (Author)

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PREFACE

The research described in this report explores the military utility of very large airplanes (over 1 million pounds gross weight) and examines several alternative fuels that could be used by such airplanes. The research was conducted jointly by Rand and the Aeronautical Systems Division of the Air Force Systems Command under the Deputy for Development Planning (ASD/XR). L. W. Noggle (ASD/XRL) coordinated the Air Force elements of the study. W. F. Hederman of Rand examined the safety and environmental aspects of nuclear-powered airplanes, and R. E. Horvath, also of Rand, the energy implications of the nuclear fuel cycle.

This analysis of the military applications of very large airplanes is an extension of research initiated in early 1974 at the request of Rand's Air Force Advisory Group and the Air Force Chief Scientist (then Dr. Michael Yarymovych), acting in his capacity as chairman of the Air Force Energy R&D Steering Group. The general objective of this research was to identify R&D programs that, in the near term, would lessen and, in the far term, perhaps would eliminate the Air Force's total dependence on aviation fuels derived from petroleum. This research is summarized in J. R. Gebman and W. L. Stanley, with J. P. Weyant and W. T. Mikolowsky, *The Potential Role of Technological Modifications and Alternative Fuels in Alleviating Air Force Energy Problems*, The Rand Corporation, R-1829-PR, December 1976. That report describes the cost and energy implications of alternative aviation fuels, implications that pertain directly to the present work; it also discusses the near-term technology options for reducing Air Force jet fuel consumption and the possible longer-term benefits of being able to utilize jet fuels (JP) derived from various primary energy resources (e.g., petroleum, coal, oil shale).

In mid-1974, the Chief Scientist requested that the initial detailed assessment of alternative aviation fuels be made in the context of the potential military applications of very large airplanes--a request that served as the impetus for the present work. Thus not only energy considerations but also the increased capability which may be provided by very large airplanes have motivated this research.

The present work was performed as part of a Project AIR FORCE (formerly Project RAND) applications analysis of very large airplanes under the research project entitled "Technology Applications Research." This is the final report on that task.

The research results presented here should assist the Air Force to formulate policy with respect to future aviation fuel options and also to develop the requirements for advanced-technology large airplanes. The report should be of interest to long-range planners in the Air Staff and Air Force Systems Command, to future systems and operational requirements personnel in the Military Airlift Command, Strategic Air Command, and Tactical Air Command, and to the Air Force laboratories.

* * * * *

Because of the length of this report, some readers may wish to skip certain sections. For example, readers not interested in analytical details pertaining to airplane design, cost, and energy consumption may proceed from Section II to Section VII with little loss of continuity. It is recommended that such readers also read the first part of Section IV in order to familiarize themselves with the terminology used in this report. Appendixes A through G contain technical details of primary interest to specialists in those areas. Those readers who intend to restrict themselves to the Summary should also consider the final section, which contains detailed recommendations. The summary and conclusions have also been published separately as R-1889/1-AF, *An Evaluation of Very Large Airplanes and Alternative Fuels: Executive Summary*.

CONTENTS

SUMMARY

Air Force interest in very large airplanes (VLAs) is motivated principally by the potential for increased capabilities that such vehicles might provide. For example, a recent Air Force study--*New Horizons II*--has suggested that the capability to deploy combat units worldwide, without reliance on foreign bases, may soon emerge as a definite requirement. Such an operational capability substantially exceeds that provided by any contemporary airplane. Rather, an airplane with a maximum gross weight in excess of one million pounds (our working definition of a VLA) may be needed. Given historical trends, airplanes of this size could become operational as early as 1985.

The widespread recognition of the ultimate depletion of U.S. petroleum resources further suggests that a very large airplane might benefit from the employment of a fuel other than a conventional hydrocarbon jet fuel (JP) refined from crude oil. Indeed, such energy considerations are sufficiently important for the Department of Defense recently to direct that the concept of energy-effectiveness be included with cost-effectiveness when the relative merit of alternative weapon systems is being judged.

The specific objectives of the present study are to:

- Evaluate very large airplanes in the context of existing and potential future Air Force missions
- Determine the most attractive alternative fuel for airplanes of this type

Each of the VLAs examined in this work employs a different candidate fuel, and the candidates include nuclear fuel as well as synthetic chemical fuels. (We define a synthetic fuel as one that can be manufactured from a primary energy resource other than petroleum or natural

gas.) As a useful benchmark for our evaluation of very large airplanes, we have included in the analysis a proposed new production version, the C-5B, of a contemporary large airplane.

Our analysis provides a framework for formulating policy conclusions and recommendations with respect to very large airplanes and alternative fuels. Appropriate future research and development activities are also identified.

DESCRIPTION OF THE VLA ALTERNATIVES

A summary description of the VLA alternatives is presented below. Our view of the desirable characteristics of VLAs is given first, followed by the results of our screening analysis, which identified the most promising candidate fuels. We then describe some important attributes of the alternative airplanes that were developed and analyzed in this work.

Desirable Characteristics

Candidate applications of very large airplanes include: strategic airlifter, tanker, missile launcher, tactical battle platform, maritime air cruiser, and C^3 (command, control, and communications) platform. The viability of a VLA would be substantially enhanced (in terms of system cost and flexibility) if a single basic airframe were capable of performing two or more of these missions. Thus, the objective of this phase of the analysis was to define the aircraft performance characteristics which would be compatible with the requirements of these missions and consistent with the expected state of the art (based on historical trends) for aircraft entering the inventory in the 1985 to 1995 time frame. This was accomplished by identifying the mission that would most strongly influence airplane design and defining appropriate performance requirements for this mission, but also including any design compromises necessitated by the remaining missions.

Our analysis indicated that an airplane primarily designed for the strategic airlift role could be most easily adapted to the other mission applications. The associated airplane performance characteristics that evolved from this analysis are presented in Table S-1. In

addition, the airplane must permit the rapid installation of a three-boom tanker mission kit and be able to air-launch vehicles as large as a 100,000-lb ICBM. (This latter requirement probably implies the need for a rear-loading capability; consequently, the VLAs incorporate both front and rear cargo compartment doors.)

Table S-1

MINIMUM REQUIRED VLA PERFORMANCE CHARACTERISTICS

Characteristic	Suggested Value
Design radius[a]	3,600 n mi[b]
Design payload	350,000 lb[b,c]
Cargo compartment	
Maximum width	25 ft
Maximum height	13.5 ft
Length	220 ft
Cruise Mach number	0.75 to 0.80
Initial cruise altitude	30,000 ft
Takeoff critical field length	8,000 ft

[a]On a radius mission, the payload is off-loaded at the destination and the airplane flies the return leg without taking on additional fuel at the destination.

[b]Limit load factor of 2.25 g.

[c]Maximum payload to be carried on 3600 n mi range mission at 2.25 g.

These requirements lead to maximum gross weights in the 1.5 to 2.0 million-lb class for JP-fueled airplanes--values thought to be attainable between 1985 and 1995.

Screening Alternative Fuels

The candidate synthetic chemical fuels which survived an initial screening are listed in Table S-2. Other fuel candidates were considered for inclusion in this list (e.g., acetylene, hydrazine, monomethylamine,

Table S-2

SCREENING OF ALTERNATIVE FUELS

	Gravimetric Heat of Combustion (Btu/lb)	Volumetric Heat of Combustion (Btu/gal)	Boiling Point (°F)	Resulting Airplane Gross Weight[a] (million lb)
Synthetic JP	18,600	121,000	210	1.68
Liquid hydrogen	51,600	30,400	-423	1.22
Liquid methane	21,500	74,500	-259	1.59
Methanol	8,600	56,700	149	>3.5
Ethanol	11,000	76,000	173	>2.5
Ammonia	8,000	45,600	-28	>3.5
Gasoline[b]	19,100	112,000	257	-

[a]For 3600 n mi radius mission with 350,000-lb payload (based on unrefined conceptual designs).

[b]Included for reference only.

and propane), but a cursory examination of their characteristics indicated that none was substantially more suitable than those shown--either in terms of its physical characteristics (e.g., heat content per pound) or its expected costs.

The six candidate fuels listed in Table S-2 were further screened by developing rough conceptual airplane designs for each fuel. The resulting gross weights of those airplanes (sized to the previously described design point) are shown in the far right column of Table S-2. Observe that owing primarily to their poorer heat content per pound, the alcohols and ammonia are clearly inferior in this application.

Thus, JP, liquid hydrogen (LH_2), and liquid methane (LCH_4) were the only chemical fuels retained in the more detailed analysis. To these, nuclear propulsion was added as a fourth alternative.

Refined Conceptual Designs

Refined conceptual designs of airplanes using each of the four alternative fuels were developed by the Air Force's Aeronautical Systems

Division (under the Deputy for Development Planning). Table S-3 highlights some important characteristics of the VLA alternatives--each designated by the fuel used (i.e., the VLA-JP is the JP-fueled very large airplane). Figure S-1 illustrates their general arrangements. (A fifth alternative--the C-5B--has been included as a benchmark. The particular C-5B model described here, designated the LG5-193A by Lockheed-Georgia, is among the least complex of the several proposed C-5A derivatives.[a])

Table S-3

CHARACTERISTICS OF THE ALTERNATIVE AIRPLANES

Characteristics	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC
Weight (thousands of pounds)					
Maximum gross takeoff	769	1839	1864	1275	2660
Operating empty	362	794	872	704	1907
Design payload	216	350	350	350	350
Performance (with design payload)					
Range (n mi)	2730	6400	6500	6250	(a)
Radius (n mi)	1560	3600	3600	3600	(a)
Radius-buddy IFR[b] (n mi)	3110	5680	5570	6530	---
Radius-buddy/rendezvous IFR (n mi)	4210	7450	7500	8750	---

[a]Essentially unlimited range and/or radius capability.

[b]In-flight refueling.

Table S-3 reveals that the VLAs provide significant increases in capability compared to the C-5B.[b] However, the VLA alternatives have

[a]The C-5B data in this report are based on preliminary Lockheed estimates. Were the Air Force to procure C-5Bs, the airplane selected for production would almost certainly differ from the proposed version used here as representative of a contemporary large airplane.

[b]Performance with in-flight refueling is also displayed in Table S-3. For each alternative, we assume that the airplane is refueled by an airplane of the same type (i.e., the VLA-JP is refueled by a tanker-configured VLA-JP). A "buddy IFR" refers to a single outbound refueling and "buddy/rendezvous IFR" includes also an inbound refueling. Tanker and receiver flights are assumed to originate at the same base.

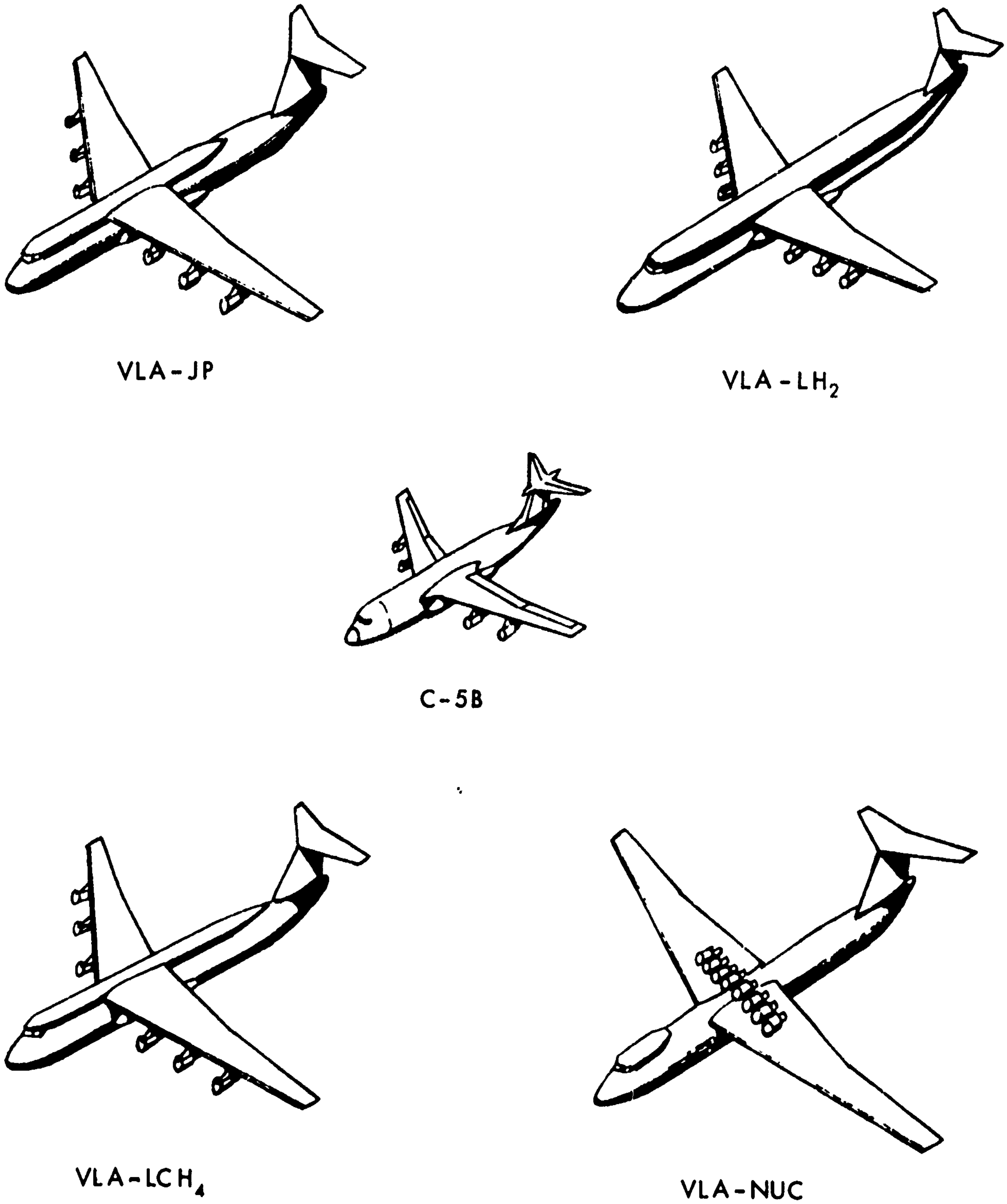

Fig. S-1—Perspective views of the alternative airplanes

such differing characteristics (e.g., the unlimited range/radius of the nuclear airplane) that a straightforward assessment of their relative merit is not possible. Our approach, therefore, has been to develop life-cycle cost and life-cycle energy consumption estimates for each alternative. By determining their effectiveness (through an appropriate metric) in a variety of mission applications, we can examine the relative cost-effectiveness and energy-effectiveness of each alternative.

We used methodologies already available in developing life-cycle cost estimates. Table S-4 illustrates the results for the VLA alternatives. They are based on the acquisition of an equal number of unit equipment (UE) aircraft (which could be interpreted as providing "equal capability" on the design-point mission) and include a representative peacetime utilization (UTE) rate.

Table S-4

LIFE-CYCLE COST ESTIMATES
(Billions of 1975 dollars)

Alternative	Acquisition Costs	20-year Operating & Support Costs	Total Life-Cycle Costs
VLA-JP	15.5	16.4	31.9
VLA-LCH_4	16.5	18.8	35.3
VLA-LH_2	13.6	21.3	34.9
VLA-NUC	32.1	24.6	56.7

NOTE: For 112 UE aircraft at 2 hours/day average UTE rate.

Estimating life-cycle energy consumption is less straightforward, since little appropriate methodology has been previously developed. Our approach was to estimate the life-cycle *total* energy consumption, as illustrated in Fig. S-2. Note that life-cycle consumption is divided into energy attributed to aircraft acquisition and energy embodied in the fuel needed for 20 years of operation.

Figure S-2 represents total, rather than just the direct life-cycle energy consumption. For example, the direct energy consumption for the 20 years of fuel is simply the energy content of the

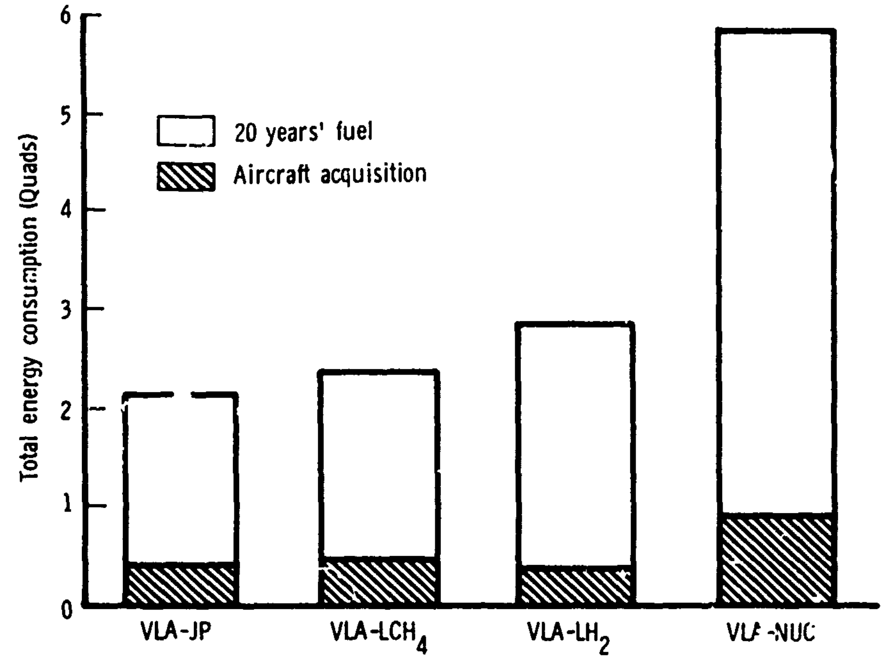

Fig. S-2 — Life-cycle total energy consumption estimates for 112 UE aircraft at 2 hours/day average UTE rate (Note: One Quad (i.e., 10^{15} Btu) is approximately equal to the energy content of 180 million barrels of petroleum.)

fuel consumed on board the airplane. Total consumption, however, includes the energy expended in the fuel supply process (liquefaction, distribution, storage, etc.). Similarly, energy expended in uranium enrichment, reprocessing, etc. is included. Our energy consumption estimates in Fig. S-2 are based on synthesizing the chemical fuels from coal (as are our fuel cost estimates). We believe this assumption is appropriate since U.S. coal reserves exceed (in terms of energy content) the sum of all other domestic fossil-fuel resources (e.g., petroleum, oil shale, etc.).

Figure S-2 illustrates the energy intensiveness of the nuclear airplane; direct comparisons with the other VLAs, however, are difficult since a different energy resource--uranium versus coal--is involved. If nuclear energy were far more abundant than coal, the greater energy intensiveness of the nuclear airplane might be of little significance. In fact, without a commercialized breeder reactor, U.S. coal reserves exceed uranium reserves (in terms of energy content) by almost an order of

magnitude; if a breeder reactor were available, this situation would be essentially reversed.

Interestingly, of the chemical-fueled alternatives, the VLA-LH_2 is the greatest energy consumer. This occurs--despite the liquid hydrogen airplane's being most efficient in terms of direct energy consumption (see tables S-2 and S-3)--because of the energy intensiveness of the processes by which LH_2 is produced, particularly the liquefaction process. For example, at least 2.6 units of energy must be expended for each unit of LH_2 delivered to the airplane; the corresponding energy ratio for synthetic JP is about 1.6.

MISSION ANALYSES

To investigate the effectiveness of the alternatives, we analyzed them in the context of the potential mission applications described earlier. A detailed analysis of the strategic airlift mission provides insights into their utility in the airlifter and tanker roles. The remaining missions, which we term station-keeping missions, have been generically investigated.

Strategic Airlift Missions

Because of the potential importance of the strategic airlift mission in providing mobility to general purpose forces, we structured our analysis of the alternatives on a detailed simulation of the deployment of Army divisions and their initial support increments to various parts of the world. For each deployment destination both range and radius missions were examined. (The assumption for radius missions is that fuel for the airlifters' return flight is either unavailable or at a premium at the destination.) The scenarios are intended to reflect the spectrum of missions that would be associated with a requirement that worldwide deployment be effected without reliance on foreign bases. In some scenarios, a certain proportion of available aircraft must provide tanker support to aircraft serving as airlifters.

Table S-5 summarizes the relative cost-effectiveness and energy-effectiveness of the alternatives for each of six scenarios. The average tons per day being deployed was selected as the measure of effectiveness; cost and energy are represented by the previously discussed

Table S-5

SUMMARY OF RELATIVE COST AND ENERGY EFFECTIVENESS FOR STRATEGIC AIRLIFT MISSIONS

Airlift Mission	C-5B	VLA-JP	VLA-LCH$_4$	VLA-LH$_2$	VLA-NUC
Relative cost					
NATO range	1.00	1.06	1.24	1.28	1.63
NATO radius	1.23	1.01	1.12	1.14	1.46
Middle East range	1.84	1.65	1.86	1.88	2.57
Middle East radius	18.52	2.67	2.38	2.32	2.32
Far East range	1.84	1.95	2.25	2.23	3.09
Far East radius	1.53	1.34	1.56	1.86	2.75
Relative energy					
NATO range	1.00	0.73	0.90	1.08	1.74
NATO radius	1.23	0.70	0.82	0.97	1.56
Middle East range	1.84	1.13	1.36	1.59	2.74
Middle East radius	18.52	1.83	1.74	1.96	2.47
Far East range	1.84	1.33	1.64	1.88	3.30
Far East radius	1.53	0.92	1.14	1.56	2.93

Most attractive   Intermediate   Least attractive

life-cycle parameters. For clarity, the relative cost-effectiveness and energy-effectiveness parameters presented in Table S-5 have been normalized to those of the C-5B in the NATO range scenario. With these definitions, the most attractive alternatives in each scenario are those with the smallest relative cost or energy consumption; for example, the VLA-JP is six percent more costly than the C-5B when examined in the NATO range scenario. The most attractive alternatives, least attractive, and those of intermediate attractiveness are indicated for each scenario.

Table S-5 is an aid to selecting the alternative that is, overall, the most attractive. To make this selection, however, one must attach

some relative importance to each of the scenarios, as well as consider cost-effectiveness versus energy-effectivness. Our principal observations from Table S-5 are that the VLA-JP is generally the most attractive alternative in terms of both cost and energy. The nuclear airplane is substantially inferior to the VLA-JP and neither of the cryogenic-fueled alternatives offer significant advantages over the VLA-JP. Note, however, that if the Middle East radius mission is discounted, the C-5B is a potentially attractive competitor to the VLA-JP.

Station-Keeping Missions

We have classified the missile launcher, tactical battle platform, maritime air cruiser, and C^3 platform applications as station-keeping missions. The required flight profile in each of these applications can be characterized by the distance from the base to the station-keeping point (the station radius) and the station-keeping duration (the time-on-station).

Some of the rationale for adapting this generic approach is provided by Fig. S-3 which associates some station-keeping missions with appropriate station radii. Note that none of the mission requires a station radius greater than about 7000 n mi. Some missions may require a long station-keeping duration (e.g., ASW) whereas others, such as the tactical battle platform, suggest much shorter time-on-station (particularly under wartime conditions when munitions are being rapidly expended).

An analysis similar to that of the strategic airlift mission was performed for each of the station radii highlighted in Fig. S-3. Both short (12 hours) and extended (324 hours) times-on-station were considered. Life-cycle cost and energy-consumption calculations were premised on a second aircraft buy. That is, it was assumed that the first buy would be for airlifters/tankers, and that additional aircraft would then be procured. Therefore, no R&D costs were associated with the station-keepers. The maximum payload tonnage that could be maintained on-station continuously (with the fleet size fixed) was selected as the effectiveness measure. This choice precludes

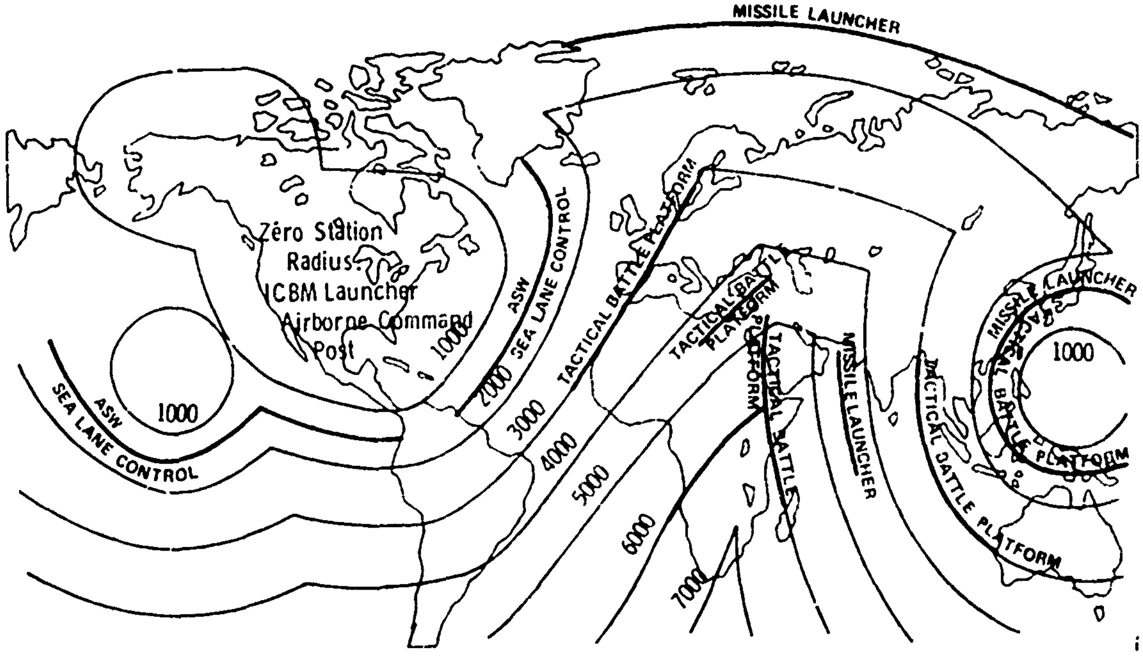

Fig. S-3 — Potential station-keeping missions matched with approximate contours of equal distance (nmi) from air bases in the United States and Guam

any insights into the merit of the station-keeping missions themselves but does provide an appropriate means for judging the relative attractiveness of the airplane alternatives when performing those missions.

A comparison of the resulting cost-effectiveness and energy-effectiveness parameters revealed that the VLA-JP was the most attractive alternative for the smaller station-keeping radii while the VLA-NUC was the most attractive for those with larger radii. All of the remaining alternatives displayed characteristics significantly inferior to these two.

The relative cost-effectiveness behavior of the VLA-JP and VLA-NUC is more explicitly detailed in Fig. S-4. (Again, some

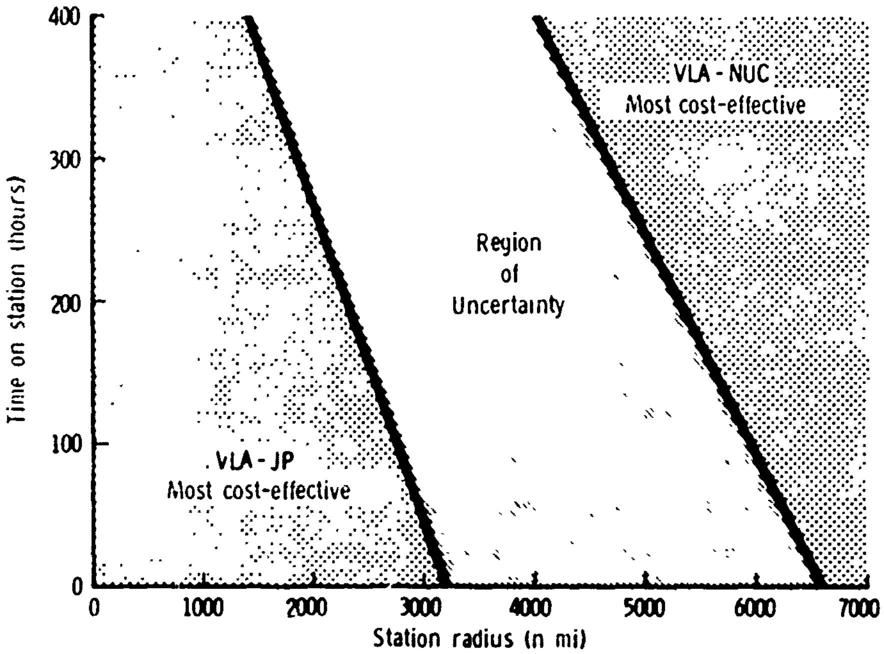

Fig. S-4 — Comparison of the VLA-JP and VLA-NUC in the station-keeping role

fraction of the VLA-JP fleet serves as tankers.) In terms of effectiveness, the VLA-NUC is superior only at the very largest station radii. Within the "region of uncertainty" depicted in Fig. S-4, either alternative can be argued to be the most cost-effective--depending on one's perspective (e.g., whether or not costs are discounted to reflect a time preference for expenditures) or the operational concept employed.

It is apparent from Fig. S-4 that the VLA-NUC begins to dominate the VLA-JP at station radii greater than 4000 n mi. Interestingly, Fig. S-3 suggests that most of the large-radius missions are tactical battle platform applications. As noted previously, these applications imply a limited station-keeping duration; as shown in Fig. S-4, shorter time-on-station tends to be an unfavorable result for the VLA-NUC.

POLICY CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and associated recommendations pertaining to alternative fuels and very large airplanes stem from the above analysis.

Conclusions

Regarding the most attractive fuel alternative:

- o Overall, a conventional hydrocarbon jet fuel (derived from either petroleum, oil shale, or coal) remains the most attractive fuel for military aircraft.
- o Liquid hydrogen and liquid methane will offer little potential as military aircraft fuels, at least, until U.S. petroleum, oil shale, and coal resources are approaching exhaustion. Associated analyses suggest that coal reserves will not be significantly depleted before the second quarter of the next century.
- o Nuclear propulsion for aircraft is only attractive for station-keeping missions requiring large station radii (greater than 4000 n mi).[a]

Regarding the potential of advanced-technology very large airplanes compared to contemporary airplanes:

- o Very large airplanes may not be substantially more cost-effective for some strategic airlift mission applications.

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[a]Modification of design constraints imposed upon the VLA-NUC could enhance its attractiveness. Specifically, allowing the nuclear airplane to take off and land with the reactor in full-power operation (perhaps with some assistance from chemical fuel) could result in a substantial reduction in gross weight. On the other hand, much uncertainty exists in the weight estimates of the nuclear reactor system. For example, more stringent crash containment criteria might result in a still heavier reactor system.

- If a worldwide deployment capability (without reliance on overseas bases) is required, then the attractiveness of very large airplanes is manifest--particularly, if fuel availability at the destination is uncertain.
- For station-keeping applications, very large airplanes are clearly superior, and this superiority becomes increasingly dominant with large station radii. (Of course, the increased vulnerability attributable to performing a given mission with a small number of large airplanes will somewhat lessen the strength of this conclusion.)

Note, however, that we have not concluded that the design constraints (range, payload, etc.) used in our analysis form a definitive requirement for an airplane of this size. Rather, the analytical results suggest that an advanced technology airplane with significantly greater capabilities than those of any existing equipment is a promising future option. The ultimate resolution of how large such an airplane should be, and what capabilities it should possess, must await further analyses.

We believe that these conclusions are substantially strengthened by our analytical approach. We resolved uncertainties in favor of the cryogenic and nuclear-fueled very large airplanes rather than the JP, and in favor of the C-5B rather than the VLAs. That the VLA-JP still appears to be the most attractive alternative is, in our view, a powerful result.

Recommendations

Regarding alternative fuels:

- The Air Force should not actively conduct R&D aimed at the introduction of cryogenic fuels for military aircraft scheduled to enter the inventory before the end of the century.

- Nuclear propulsion should only be pursued if firm mission requirements emerge for a large-radii station-keeping capability and if research has demonstrated that public safety can be assured.
- The Air Force (and the Department of Defense) should take aggressive action to assure the future availability of JP for military aircraft.

Regarding advanced-technology large airplanes:

- The Air Force should maintain a strong and active interest in advanced-technology large airplanes.
- Further study is needed to identify the optimum design constraints for military applications.
- The possibility of a compromise aircraft--one that would meet the requirements of commercial air cargo operations as well as military requirements (particularly for strategic airlift)--should be explored.[a]
- Analyses addressing in greater detail the desirability of and need for the various station-keeping missions appear appropriate.
- Areas of research which may benefit advanced-technology large airplanes include:
  - Propulsion (turbine engine technology, propfans)
  - Aerodynamics (laminar flow control, thick supercritical wings)
  - Structures (composites, aeroelastic effects of high aspect ratio wings)

Of course, any such Air Force technology R&D activities should aim to be cognizant of and complement related NASA work on fuel-conservative aircraft technology.

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[a]Such a study is presently being sponsored by the Air Force's Aeronautical Systems Division under the Deputy for Development Planning.

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Of course, any errors or omissions remain the sole responsibility of the authors.

I. INTRODUCTION

The primary purpose of this report is to present a detailed comparison of alternatively fueled very large airplanes in the context of a spectrum of Air Force missions. The research it describes was jointly performed by Rand and the Aeronautical Systems Division (ASD/XR) of the Air Force Systems Command.

In this introductory chapter we will discuss the events that motivated this inquiry, state our research objectives, and outline the structure of the report.

BACKGROUND

Many factors, most of them having their origin in the 1973 Middle East war, provided the motivation for the present study. Although ultimately all of them can be regarded as relating to U.S. national security, these can be broadly categorized as military-related or energy-related. We shall discuss these categories separately, but it should be realized that in certain areas there is considerable overlap.

Military Considerations

Between October 13 and November 14, 1973, aircraft of the Military Airlift Command (MAC) delivered 22,497 tons of equipment and supplies to Lod Airport, Tel Aviv, Israel. Both the C-141A and C-5A aircraft participated in this airlift. Of the total tonnage delivered, C-5As carried 10,757 tons (in 147 sorties) and C-141As the remainder (in 422 sorties) [1].

Although it accomplished its primary objectives, this exercise revealed several potentially dangerous shortcomings in U.S. strategic airlift capability--particularly for long-range missions. Specifically, it revealed that we might be denied overseas bases or overflight rights and that fuel for the return flight at the aerial port of debarkation (APOD) might be unavailable or of very limited availability.

Denial of Overseas Bases or Overflight Rights. To a great extent, overseas bases and overflight rights were both denied to us during the

1973 airlift. In the United Kingdom, Spain, Italy, Greece, and Turkey, the United States could not obtain diplomatic clearance to use bases which MAC usually used. Furthermore, all aircraft participating in the airlift were forbidden to overfly any land mass. In consequence, the only en route base available for refueling was Lajes Field in the Azores (Portugal), and the route through the Mediterranean had to have numerous zigzags. The few flights that originated in West Germany had also to be routed through Lajes.

At the time of writing, Portugal's political future can only be described as uncertain. In recent months, however, her leaders have indicated that the use of Lajes as an en route base for aircraft participating in operations in the Middle East may also be forbidden. Had this situation arisen in the 1973 war, the likelihood of a successful U.S. airlift operation would have been small. At that time, neither the C-5A nor the C-141A was equipped to accept in-flight refueling.[a] If all aircraft had been required to fly direct from Dover AFB, Del., to Tel Aviv without in-flight refueling, maximum payloads would have been reduced for the C-5A from 108 tons to about 50 tons and for the C-141A from 34 tons to less than 10 tons [3,4]. Clearly, such a reduction in capability would have greatly debilitated the effectiveness of the airlift operation.

Today, of course, the use of in-flight refueling would allow the C-5A to carry its maximum payload to Israel without relying on en route bases. Such an operation, however, is not necessarily straightforward. Each outbound C-5A sortie will require an in-flight refueling from a cell of three or four KC-135As in order to reach Israel with the maximum payload. A substantial number of Strategic Air Command (SAC) tankers would thus be required to support such an operation. (See Section VII for an expanded discussion of tanker requirements.)

Unavailability of Fuel at the Destination. The situation described above (i.e., denial of basing rights) could be greatly

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[a]Today, all C-5As have been modified to allow for aerial refueling. The C-141As may also be so modified in the future, as a part of the fuselage stretch program [2].

aggravated if fuel is either unavailable or in limited supply at the destination. Such a situation could arise if the fuel supply system were interrupted (e.g., maritime interdiction of seaborne tankers) or if the available fuel were required for tactical aircraft operations in the battle area.

For example, in the Israeli airlift, the total amount of fuel required for the return leg (from Lod to Lajes) exceeded the amount of equipment delivered by almost 2000 tons. Had this fuel not been available, the aircraft would have been required to fly radius missions between Lajes and Lod--in other words, depart from Lajes with a full fuel load, off-load equipment at Lod, and return to Lajes without any refueling. Again, the performance of both airplanes would be seriously degraded--their maximum payloads would be reduced to about what they could carry in nonstop Dover AFB to Tel Aviv flights.

If overseas bases are denied and fuel is not available at Lod for the return leg, the C-5A (or the C-141A, if modified to allow for in-flight refueling) could only carry significantly reduced payloads to Tel Aviv--but this would require a maximum aerial refueling effort by KC-135As.

NATO Deployment Requirements. That the C-5A and C-141A aircraft lack impressive performance capabilities for the Middle East airlift mission should not be surprising. The characteristics of both airplanes make them most suitable for strategic airlift operations in support of a NATO contingency. However, even in this instance, additional capability may be desired to lessen the time needed to deploy reinforcement divisions in a conventional NATO war [5].

The existing MAC fleet would require more than 80 days to deploy eight divisions and their initial support increments from the United States to NATO. If fuel is at a premium at the destination, the MAC fleet, consisting of 70 UE (unit equipment) C-5As and 234 UE C-141As, would require tanker support by more than 125 KC-135As.[a]

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[a]An expanded discussion of NATO deployment capability is presented in Section VII.

Realizing the need to enhance U.S. strategic airlift capability, former Secretary of Defense James Schlesinger suggested that an appropriate goal would be the capability to deploy an average of one division per week to NATO [6]. To achieve such a capability today would require additional USAF transport airplane capability (either by enhancing the capabilities of the existing fleet or by acquiring additional aircraft) and a greater reliance on aircraft in the Civil Reserve Air Fleet (CRAF).

Other Missions. Thus far, our discussion of the study's background has concentrated on the possible need for enhancing--and, in the long term, maintaining--U.S. strategic airlift capability. But an airplane suitable for use in the airlift role could also be employed in a variety of other missions.

Many organizations have suggested both strategic and tactical missions. Examples of the strategic application include airborne missile launchers [7], tanker support for strategic bombers, and airborne command posts. Typical tactical missions are the tactical battle platform for launching either manned fighters or remotely piloted vehicles (RPVs) [8,9], various maritime missions such as antisubmarine warfare (ASW) or sea-lane control [10], and as a platform for Airborne Warning and Control Systems (AWACS).

Clearly, a very large airplane is a candidate for any of these missions as well as for the strategic airlift mission.

Energy Considerations

In addition to the national defense implications of the 1973 Middle East war, related events graphically illustrated some of the energy problems facing the United States--the vulnerability of the United States to oil embargoes, the possibility of sharp increases in fuel costs, the depletion of domestic crude oil resources, and the issues associated with making a transition to other energy sources.

Vulnerability to Oil Embargo. In late 1973, the Arab members of OPEC (Organization of Petroleum Exporting Countries) instituted an embargo on crude oil exports to the United States and several nations in Western Europe. By the time the embargo was lifted in early 1974,

the petroleum supply shortfall in the United States was estimated to be about 14 percent. Most consumers recall the principal impact of the embargo to be exceedingly long queues at gasoline pumps. However, impacts throughout the economy were severe. The Federal Energy Administration has estimated that the embargo caused a $10 to $20 billion drop in gross national product and, at its peak, resulted in 500,000 additional people being unemployed [11].

The impact of the 1973 embargo on the Department of Defense (DoD) was perhaps less dramatic, but nonetheless significant. During the period of the embargo, the Defense Supply Agency (DSA) experienced difficulty in obtaining needed quantities of jet fuel [12]. Despite reduced jet-fuel consumption resulting from lessened flying activity, the difficulty DSA encountered required a substantial drawdown of pre-positioned war resources. The situation was not alleviated until provisions of the Defense Production Act were invoked in November 1973. Indeed, the precipitous decline of DoD energy consumption (from an average of 773,000 barrels per day in FY 73 to about 550,000 barrels per day in the fall of 1974) was not reversed until the first deliveries were made under the Defense Production Act.

Besides these very real problems associated with an oil embargo, the Air Force, as a particularly visible consumer of energy, might, in a similar situation, be perceived by the public as a consumer of petroleum supplies that more properly should be diverted to domestic use. Of course, the importance of this perception is very much related to the magnitude of the supply shortfall and concomitant dislocations in the domestic sector.

Increased Fuel Costs. Before the 1973 embargo, oil imported from the Persian Gulf was priced at approximately $4.65 per barrel. After the embargo was lifted in the spring of 1974, the average price was approximately $11.00 per barrel [12], and since then has been increased by OPEC to about $14.00 per barrel.

The impact on the Air Force budget of these increases has been somewhat smaller since the input crude oil is drawn from domestic as well as imported sources. The price per gallon (to the Air Force) of

JP-4[a] has increased from 11 cents in June 1973 to 35 cents in July 1974. In July 1975, the average price was about 42 cents per gallon [13]. These increases represent nearly a quadrupling of the cost of jet fuel to the Air Force in only two years.

The impact on the budget has been no less severe. Even with savings from conservation (including reduced flying activity), the two supplemental requests by DoD for petroleum totaled almost $1 billion in FY 74.

Depletion of Domestic Crude Oil Resources. In addition to the energy-related problems discussed above, the events surrounding the 1973 Middle East war also served to increase the level of awareness of our long-term energy problems. The most visible long-term problem, and the one commanding the greatest attention, is the impending depletion of domestic reserves of crude oil.

That domestic crude oil resources will eventually be exhausted is undeniable; one of the critical issues, of course, is the rate of exhaustion. The U.S. Energy Research and Development Administration's (ERDA's) latest estimates for domestic oil production is illustrated in Fig. 1. Note that with enhanced recovery techniques, and by including Alaskan North Slope oil, production can be maintained at or near the 1970 level until the beginning of the 1990s [14].

To appreciate fully the implications of Fig. 1, the demand for energy through the end of the century must also be considered. The level of demand clearly depends on many factors--including the domestic energy supply. ERDA has attempted to explore the range of future energy requirements by forecasting energy consumption for six different scenarios or "energy futures";[b] this projection is

[a]JP is the military designation for jet fuels currently refined from crude oil; as described later in this report, JP can also be synthesized from coal or oil shale.

[b]Each scenario represents an emphasis on a selected technology or combination of technologies.

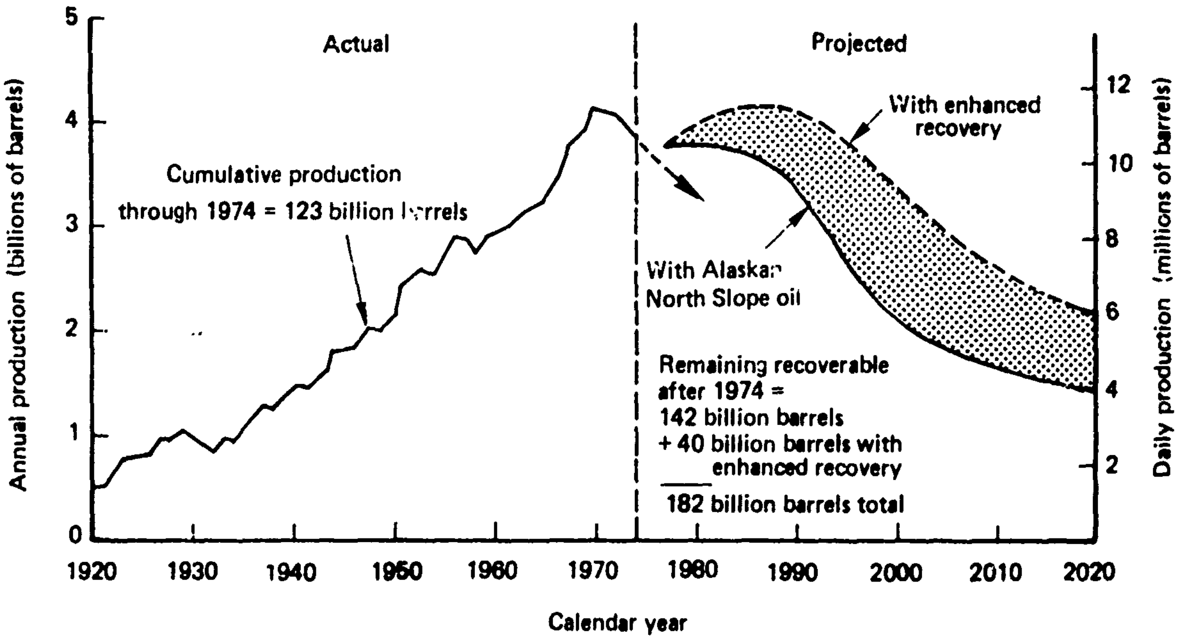

Fig. 1 — Domestic production of both crude oil and natural gas liquids [14]

shown in Fig. 2. These forecasts for the year 2000 range from a low of 120 Quads (quadrillion or 10^{15} Btu's)[a] to a high of about 170 Quads compared with a total consumption of about 71 Quads in 1975. Total U.S. energy use has been projected by others to be as high as 225 Quads in 2000 [15].

Despite the uncertainty in future energy supply and demand, one fact emerges clearly. In 1975, nearly 50 percent of total U.S. energy demand was met by petroleum, with domestic petroleum resources accounting for about one-third of the total. Figure 1 indicates that, at best, domestic petroleum production will remain nearly constant (at about 22 Quads per year) through the remainder of the century. Thus, to meet the energy demand levels shown in

[a]The energy content of 180 million barrels of petroleum is approximately equal to one quadrillion (i.e., 10^{15}) Btu's.

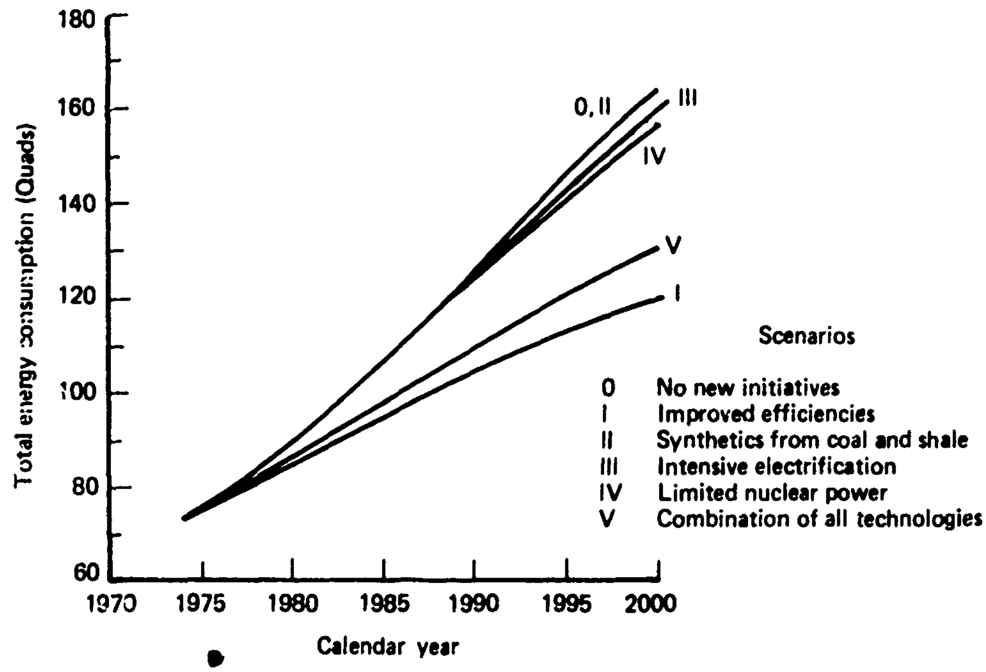

Fig. 2 — Projected total U.S. energy consumption [17]

Fig. 2, the United States must begin to rely much more heavily on energy resources other than domestic petroleum. To date, much of this excess demand has been met by increasing petroleum imports.

Making the Transition to Nonpetroleum Energy Resources. Before discussing the inevitable transition from primary reliance on petroleum to reliance on other energy resources, we believe it useful to indicate the time frames that are being considered. For this purpose, we use the terminology recently suggested by Naill [16], who divides the growth of U.S. energy consumption into three periods.

- Historical Period--Characterized by an exponential growth in energy consumption, a growth predicated on the exploitation of conventional low-cost energy resources such as crude oil and natural gas.

- Transition Period--Begins with the approaching depletion of conventional resources and ends when energy demand is largely satisfied by ultimate energy resources.
- Stable Period--Energy demand is satisfied by non-depletable and relatively pollution-free ultimate energy resources. Total energy requirement is moderated by a stabilization of population growth.

From our earlier discussion, we can be relatively certain that the United States has already entered the transition period. But before describing that, we will first discuss the stable period.[a]

A consideration of the foreseeable technology dictates that the most likely ultimate energy resources are controlled thermonuclear reactors (i.e., fusion) and solar energy (including wind energy, energy from the biomass, etc.). The prospects for controlling the fusion reaction are uncertain but promising. However, even the most optimistic assessments do not suggest the commercialization of the technology before 2000 [17]. Solar power has a somewhat different future. Today, many situations exist in which solar energy can be economically exploited--for example, to heat water for residential use [18]. Before such applications (including residential space heating and cooling) can make an appreciable contribution to meeting total energy demand, several decades must pass in which emphasis is placed on the construction of homes using solar energy or retrofitting existing buildings with solar energy devices. Advanced applications of solar energy, such as an economical central-station power plant, require technology beyond today's state of the art. To summarize, the stable period is not likely to begin before 2000; it will probably not fully arrive until at least the middle of the next century.

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[a]We are assuming, perhaps heroically, that the stable period will eventually come into being. Many other scenarios can be envisioned that halt or reverse the exponential growth in energy consumption, but, since most portend doom or catastrophe, they seem inappropriate for rational planning. In our view, the transition scenario described in this work is, at least qualitatively, the most sensible.

Our immediate problem is how do we get there from here. In the transition period, greater reliance will have to be placed on more abundant, though nonrenewable, energy resources. Without doubt, coal and uranium are the two most abundant economically recoverable domestic energy resources [14][a] and will clearly play important energy roles in the transition. To illustrate, Fig. 3 is a recent projection of primary energy resource consumption

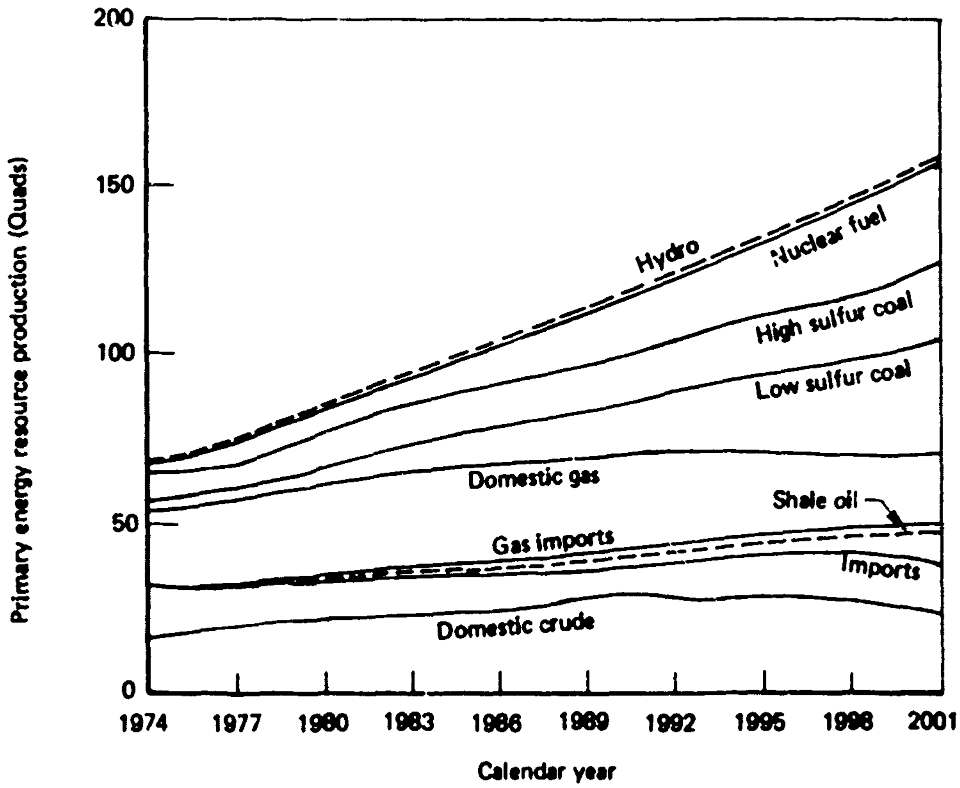

Fig. 3 — Projected total U.S. energy supply [15]

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[a]Reference 19 contains a more detailed description of the availability of nonpetroleum energy resources. (See also Section VI.)

through the year 2000. Note that the total energy production in 2000 (about 150 Quads) shown in Fig. 3 is consistent with the range of demand forecasts displayed in Fig. 2. The specific energy scenario shown in Fig. 3 presumes a moderately heavy emphasis on synthetic fuels from coal and oil shale--with these resources (as liquids and gases) accounting for nearly 25 Quads in 2000. Note also the growth in nuclear power included in Fig. 3. The contribution of coal and uranium to the total supply is shown to increase from less than 20 percent of total energy production in 1975 to more than 50 percent in the year 2000.[a]

Figure 3 is not intended to reflect the most likely or the most attractive scenario for the transition period. Rather it has been included to illustrate how patterns of U.S. energy production (and, consequently, energy consumption) might emerge in the next several decades. Our main message is that in the future petroleum and natural gas resources are not likely to expand, whereas the use of coal and/or uranium will almost assuredly increase.

ORIGINS OF THE PRESENT STUDY

Thus, the events of the 1973 Middle East war had significant effects on Air Force operations, and since the war, the marked increases in the price of jet fuel and the difficulty of obtaining fuel during the embargo have underscored the seriousness of the energy situation.

Early in 1974, Rand's Air Force Advisory Group (AFAG) requested that Rand examine the implications to the Air Force of the emerging world energy situation. Consideration was to be given to both near-term and long-term problems. The initial efforts of this study concentrated on the attractiveness, in terms of cost as well as energy,

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[a]In Fig. 3, total imports of crude oil and natural gas are projected to be nearly constant through 2000. Note that an alternative to expanded reliance on coal and uranium is to expand the quantity of imports. Such a policy might be unacceptable because of the threat of future oil embargoes as well as the possibility of capricious changes in the price of imported oil.

of various technological options (e.g., engine retrofitting) that could be employed to reduce the jet fuel consumption of the existing Air Force fleet [19]. For the longer term, the possible use of alternative fuels derived from primary energy resources other than petroleum or natural gas was seen to be of obvious interest.

Also early in 1974, the Vice Chief of Staff directed the Air Force Chief Scientist, then Dr. M. I. Yarymovych, to "organize and chair a Steering Group to develop the research and development plans and to monitor studies on the long-range implications of the energy shortage upon the Air Force's ability to carry out its mission." The resulting "Air Force Energy R&D Steering Group" was charged [20], among other things, with making:

- o Projections of the usage of synthetic fuels and definitions of their desirable characteristics.
- o A review of potential new propulsion systems, both those using synthetic fuels and those using nonhydrocarbons, including hydrogen.
- o Conceptual analysis of new systems using nonhydrocarbon fuels.

Preliminary results of Rand's analysis of the near-term technological options and its research plan for examining the longer-term alternative fuels option were briefed to the Steering Group in the spring of 1974 [19].

In mid-1974, Dr. Yarymovych requested that the initial detailed evaluation of the alternative fuels be made in the context of various mission applications of very large airplanes. The primary motivation for this approach, as should be clear from our earlier discussion, was the potential need for an airplane with greater range and/or endurance capability than contemporary equipment. Furthermore, previous studies had indicated that many of the candidate alternative fuels (e.g., liquid hydrogen [21] or nuclear propulsion [10]) would be most attractive for applications in very large airplanes.

The analysis of mission applications of very large airplanes was jointly conducted by Rand and the Aeronautical Systems Division (under the Deputy for Development Planning, ASD/XR). This arrangement permitted maximum use to be made of ASD's extensive computer-aided airplane design capability.

The final report of the Air Force Energy R&D Steering Group contained a recommendation that also influenced the present work. Specifically, it recommended that energy-effectiveness be made a consideration in weapons system acquisition [20].

In the words of the report:

> *Owing to the rising cost of energy and its impact on life-cycle costs, the most cost-effective alternative now may also be the most energy-effective. In some cases, however, cost benefits to be derived from energy savings will not significantly affect the cost-effectiveness; and thus, where cost and energy concerns are divergent, one must decide which alternative will produce the greater benefit to the nation.*

This recommendation was subsequently endorsed by the Secretary of Defense in the Phase II Report of the Defense Energy Policy Council [12]. Thus, the concept of energy-effectiveness has been included in the present study.

In addition, the recent *New Horizons II* study has emphasized that consideration should be given to the potential of very large airplanes satisfying the kinds of mission requirements we described earlier [22].

STUDY OBJECTIVES

The principal objectives of the study were to:

- Evaluate very large airplanes in the context of existing and potential future Air Force missions.
- Determine the most attractive alternative fuel for airplanes of this type.

With those specific objectives accomplished, it was also possible to identify promising avenues for future research and development.

The first study objective is to compare various very large airplanes using alternative fuels in a wide spectrum of mission applications. For this study, we have defined a very large airplane as one with a gross weight in excess of one million pounds. Gross weights of this magnitude are commensurate with what can be expected of airplanes that might become operational in the 1985 to 1995 time frame [23]. To enhance the comparison and provide a useful benchmark, we have included a contemporary large airplane, the C-5B, in our mission analysis. No attempt has been made to compare the alternative very large airplanes with other means of accomplishing the same mission. For example, one of the missions we have examined is the strategic airlift of Army equipment for NATO reinforcement. Other alternatives which could be considered are sealift or pre-positioning of equipment. In spite of this limitation in scope, we believe that the study results provide meaningful insights into the potential of very large airplanes for the mission applications examined.

The second objective is to determine the most attractive alternative fuel for very large airplanes. A wide variety of chemical fuels as well as nuclear propulsion have been considered as possible alternatives. Of course, we are mainly interested in fuels that can be derived from a primary energy resource other than petroleum or natural gas. Indeed, all of the chemical fuels included in our detailed analysis can be synthesized from coal. Note that each of the resulting alternatives (chemical fuels from coal or nuclear propulsion using uranium) is premised on primary energy resources that are expected to become increasingly important during the next fifty years.

ORGANIZATION OF THIS REPORT

Candidate mission applications for very large airplanes are discussed in Section II; mission requirements are identified which, in turn, define the desirable airplane performance characteristics. Section III presents a screening of the available chemical fuels; this screening limited our more detailed analysis to only JP, liquid methane,

and liquid hydrogen, as well as nuclear propulsion. In Section IV, the important characteristics of the refined conceptual airplane designs developed by ASD are described. Life-cycle costs are discussed in Section V, and life-cycle energy consumption in Section VI.

Section VII contains the results of our detailed analysis for the strategic airlift mission. A similar comparison for various station-keeping missions is presented in Section VIII.

The conclusions are delineated in Section IX. Finally, in Section X, the recommendations on future research and development are presented.

The main text is supported by a number of appendixes. Details of airplane design and propulsion system design are contained in Appendixes A and B, respectively. Appendix C discusses the performance of the chemical-fueled airplanes with aerial refueling. Details of our estimates of life-cycle costs are included in Appendix D; cost and energy consumption aspects of the nuclear fuel cycle are discussed in Appendix E. The strategic airlift mission analysis backup is contained in Appendix F with similar material in Appendix G for the station-keeping missions. Appendix H discusses some of the important auxiliary issues (i.e., issues other than cost, energy, and military effectiveness) associated with the alternatives, and Appendix I presents a brief discussion of some of the unique problems associated with nuclear-powered airplanes.

II. DESIRABLE VLA PERFORMANCE CHARACTERISTICS

We begin this section with a brief description of the candidate mission applications of very large airplanes. We then identify the mission or missions that serve as constraints in defining the desirable airplane characteristics, on the assumption (for purposes of the present work) that the design of the very large airplane should provide for a multimission capability. The remainder of the section is devoted to defining some capabilities desired in very large airplanes and identifying the associated design constraints.

CANDIDATE MISSIONS

The potential military applications of very large airplanes encompass a wide variety of mission types--some of them routinely flown by the Air Force today, others merely suggested by various organizations for consideration in future force structures. Below are the candidate roles regarded as most likely for very large airplanes.

1. Heavy airlifter
2. Tanker
3. Missile launcher
4. Tactical battle platform
5. Maritime air cruiser
6. Command, control, and communications platform (C^3)

Each of these missions[a] is discussed below, together with some of the performance requirements they suggest.

Heavy Airlifter

The first, and perhaps most obvious, role for the very large airplane is as a heavy airlifter. We should differentiate between two

[a] In subsequent sections of this report, candidates 3 through 6 are referred to as "station-keeping missions."

types of airlift--strategic and tactical. Today's strategic airlifters are the C-5A and the C-141A; various models of the C-130 provide most of the U.S. tactical airlift capability. Very large airplanes appear to be applicable only to the strategic airlift mission.[a]

The very large airplane can be envisioned as the eventual replacement for the C-5A (and perhaps the C-141A). As such, a capability to carry outsized equipment[b] (e.g., main battle tanks, large helicopters, etc.) must be provided. In addition, however, cargo compartment size and shape should be compatible with palletized loads, as well as air/surface intermodal containers. This not only enhances the utility of the airplane for resupply missions but also leaves open the possibility of a derivative airplane's being employed as a commercial air freighter. Of course, as a commercial airplane in the Civil Reserve Air Fleet, this VLA variant would have the potential to enhance military airlift capability still further.

Tanker

The second candidate listed is the tanker mission. Several somewhat different potential applications should be considered. These include:

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[a]The C-5A originally was intended to serve in both strategic and tactical roles and, for example, was provided with a soft-field landing capability. Experience has shown, however, that the requirements of strategic and tactical airlift are essentially incompatible. At present, no plans exist to use the C-5A as a tactical airlifter.

The view that strategic and tactical requirements are incompatible has been reinforced by recent consideration of the possibility of employing some of the longer range versions of the C-130 (e.g., the "E" model) to augment strategic airlift capability. The relatively limited range of a tactical airlifter seems to preclude its substantially enhancing strategic airlift capabilities. However, future versions of the proposed advanced medium STOL (short takeoff and landing) transport, AMST, may provide a supplemental strategic capability.

[b]Outsized equipment is presently defined as equipment that is too large to be loaded into a C-141A. We will later expand on this point.

- o In-flight refueling of strategic airlifters
- o In-flight refueling of strategic bombers
- o In-flight refueling of tactical fighters (either during fighter deployments or for extending endurance in tactical operations)
- o Emergency delivery of aviation fuel for contingency operations

Such tanker missions are being routinely flown today by KC-135As and KC-97s. Note that the relatively high density of JP-type fuels (usually more than '0 pounds per cubic foot) suggests that tankers will invariably be weight-limited rather than volume-limited as is often the case for heavy airlifters. (Some types of Army equipment often average much less than 10 pounds per cubic foot.)

Missile Launcher

An offensive-missile launcher is the next mission candidate. In this instance, two possibilities exist: a strategic carrier for launching intercontinental ballistic missiles (ICBMs), or a standoff carrier of air-launched cruise missiles (ALCMs) for either strategic or tactical operations.[a]

Most strategic concepts in this category suggest the desirability of an airborne alert as a means of increasing survivability. The airborne alert can either be maintained continuously (though perhaps at levels below maximum capability) or be employed only during contingencies, with some of the missile launchers usually being maintained on ground-alert in peacetime.

In general terms, the missile launcher mission has different characteristics for the two types of weapons. For ICBMs, the range and penetration characteristics of the missile may permit the airplane to maintain the airborne alert while loitering relatively close to the home airfield. ALCMs, on the other hand, penetrate at low level and

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[a]The difference between this tactical application and the tactical battle platform (discussed next) is that, in the latter instance, the intention is to control and retrieve the launched vehicles.

have a comparatively limited range. Thus, the carrier airplane must cruise to an appropriate standoff range before commencing the loiter phase of the mission. Depending on the location of the home base and the desired targets, the cruise phase of the mission could cover a considerable distance (see Section VIII). Because of these loiter requirements, the endurance characteristics of the airplane need to be considered along with its range characteristics. Of course, the loiter phase is only important when the weapon system is being employed in an airborne alert context (e.g., a show of force). In a wartime situation, missile launching would likely commence as soon as the standoff range is achieved.

Tactical Battle Platform

The fourth candidate role for very large airplanes is the tactical battle platform. The weapons system launched (and retrieved) by the platform could be remotely piloted vehicles or manned microfighters. Alternatively, an advanced weapons platform (e.g., high-powered lasers or particle-beam systems) should be included as a possibility for this mission role. In any case, the command and control function would probably be located on the launch platform.

The type of mission profiles flown by the platform is dependent on the distance between the home airfield and the area of tactical operations. If the distance is quite large, the cruise-to-station phase of the mission could be important. In any case, the tactical battle platform would be required to loiter on-station for some period of time--at least from launch until recovery.

If the objective of the mission is a "show of force," then the required loiter time could be substantial. On the other hand, if the battle platform is actively engaged in tactical operations, loiter time is likely to be limited by the need to replenish consumables (e.g., fuel for RPVs, munitions, etc.); relatively brief loiter times can be envisioned in this case.

Maritime Air Cruiser

We have included several potential maritime roles in this category. The most significant are:

- o Antisubmarine warfare missions
- o Picket defense missions
- o Sea-lane control missions

All of these missions have certain common characteristics: The loiter periods (or, in the case of ASW, tracking periods) would probably be of long duration and, during loiter, the characteristic distances from land bases will generally be less than 2000 n mi.

Note that considerable overlap exists between the maritime missions and certain of the previously discussed missions. For example, the sea-lane control missions could be regarded as an application of either the tactical battle platform or the ALCM launcher.

Command, Control, and Communications (C^3) Platform

The final role listed is the C^3 mission. Obvious examples of this type are the airborne command post and the airborne warning and control system (AWACS) missions. The former is today being performed by versions of the Boeing 747 and KC-135, while a derivative of the Boeing 707 airframe has been proposed (and is currently in production) for the latter.

Again, the characteristics of the mission profile for these applications depend on specific operational concepts. In almost all cases, however, extended loiter times are required.

MULTIMISSION CONSIDERATIONS

Several different airplane configurations could be envisioned for satisfying the needs of the missions we have just described. *For the present study, however, we have chosen to define a configuration that is compatible with the requirements of all of these missions.*[a]

[a]Except, as noted, the very large airplane does not appear to be suitable for tactical airlift.

Two very important cost considerations account for this approach. First, the development costs of any next-generation large airplane are expected to be substantial. The nonrecurring development costs for the C-5A exceeded one billion dollars (in 1975 dollars). Indeed, our own estimates suggest that the total development costs of a very large airplane could exceed three billion dollars. Clearly, if more than one of the potential missions emerge as definite requirements, enormous savings in development costs would result if the same basic airplane could be employed (see also Section VIII). We are, of course, not the first to recognize the potential savings which can be attributed to possessing an airplane with a multimission capability [24].

A second, and no less important, cost aspect is the lower average unit flyaway cost that results from buying a greater number of airplanes. For example, if the average unit flyaway cost for 50 airplanes is 75 million dollars, a typical average unit cost of about 54 million dollars could be expected for 200 airplanes--assuming an 85 percent slope for the cost-quantity curve. (For specific details relating to the airplanes examined in the study, see Appendix D.)

To provide a multimission capability, the varying requirements of the candidate missions must be considered. One approach is to envision the design that emerges if an airplane is conceived that fully satisfies the requirements of a particular mission. The performance of this design in the other missions would then be tested. By repeating the process for each candidate mission, the constraining mission could be identified.

STRATEGIC AIRLIFT--THE CONSTRAINING MISSION

Our analysis has indicated that a very large airplane designed primarily as a strategic airlifter would be capable of performing any of the candidate missions.[a] Below, we describe a representative set

[a]Some thought will reveal that an airplane designed for any of the other candidate missions would lack such a capability. For example, the cargo compartment of an airplane designed specifically for the tanker mission would almost certainly be unsuitable for airlifting outsized equipment.

of desirable airplane characteristics that will be commensurate with the present objectives. The principal characteristics which must be defined are:

- o Design range
- o Design payload
- o Cargo compartment dimensions
- o Cruise conditions
- o Airfield considerations
  - -- Takeoff distance
  - -- Landing distance
  - -- Runway bearing

When conflicts exist between strategic airlift mission requirements and readily identifiable requirements of some other mission, our resolution of the conflict will be explained.

Design Range

Before selecting an appropriate design range, a brief digression to define some terminology will prove useful. Figure 4 illustrates the typical shape of the range-payload curve for a chemically fueled airplane. The X-point represents the range with maximum payload, where the structural limits of the airplane determine maximum payload. As one moves down the curve from the X-point to the Y-point, payload weight is exchanged for fuel weight, and range (at reduced payloads) increases. The Y-point corresponds to the condition in which all fuel tanks are full; further reductions in payload therefore result in only a relatively small increase in range (the solid line rather than the dashed). Of course, depending on the specific airplane design, the Y-point can go to a zero payload condition (hence the dashed line to the range axis). Note that the gross takeoff weight between the X-point and the Y-point will always be equal to the maximum gross takeoff weight.

Generally, an airplane is sized by selecting a single point representing the desired design range and design payload, and usually

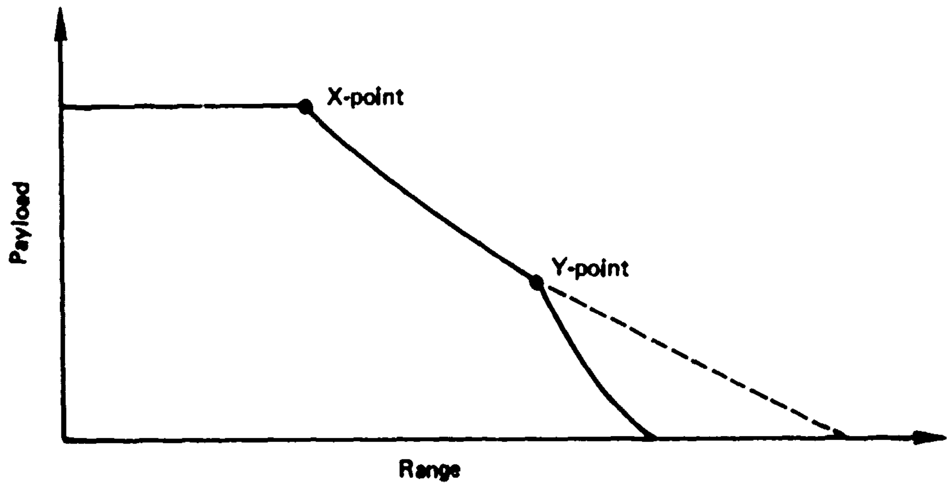

Fig. 4 — Typical range-payload characteristics for a chemical-fueled airplane

this design point is either an X-point or a Y-point. *In the present study, the design point will generally lie between the X-point and the Y-point.* Thus, the design payload will be less than the maximum payload.

Our reason for using this approach will be apparent from what follows.

Selecting a design range for the strategic airlift mission is not a straightforward proposition. We feel that the following geopolitical factors need to be considered:

- o Defense of NATO is a cornerstone of U.S. foreign policy; hence providing a significant reinforcement capability for NATO contingencies is a primary objective of U.S. strategic airlift forces.
- o Depending on the nature of future conflicts, fuel at the deployment destination (for the return flight) may either be unavailable or at a high premium.

- The emerging world political situation may require a worldwide deployment capability nat does not rely on bases outside of U.S. terrritory for en route refueling.

On the surface, these factors seem to lead to requirements that are incompatible.

Our approach has been to specify a design range that, at the least, will come nearer than any contemporary large airplane to satisfying all of these potential requirements.

Meeting all three of the requirements might initially seem to require the airplane to have a design range of at least 10,000 n mi (or perhaps even a design radius of 10,000 miles, if fuel availability at the destination is uncertain). However, consider the global distances depicted in Fig. 5. The contours, approximately equidistant,

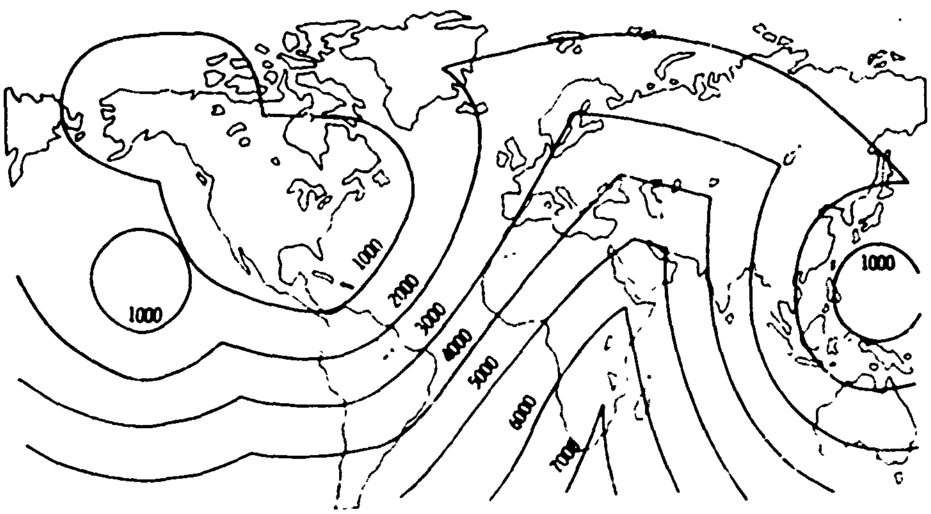

Fig. 5 — Approximate equidistant contours (in nmi) from Air Force bases in the conterminous United States, Alaska, Hawaii, and Guam

from bases in the United States (including Alaska and Hawaii) and from Andersen AFB on Guam in Fig. 5 show that there are essentially no land masses (except parts of Antarctica) farther than about 7000 n mi from a base. Thus, a 7000 n mi figure appears to us to be the useful upper limit for design range or design radius.[a]

Given this view of the range required to provide a worldwide deployment capability, we selected a design *radius* requirement of 3600 n mi. Such a radius is primarily derived from the NATO reinforcement requirement--it allows for the delivery of the design payload from Dover AFB (Del.) to Frankfurt, Germany, and return without refueling in Europe. When flying range missions (i.e., refueling at the destination), airplanes with a 3600 n mi radius capability can deliver their design payload a distance of 6000 to 6500 n mi. As Fig. 5 shows, such a range provides essentially worldwide coverage. If fuel is not available at the destination, aerial refueling will permit radius missions of more than 3600 n mi. (In Section IV, we show that with outbound and inbound in-flight refuelings, the mission radius with the design payload would generally be in excess of 7000 n mi.)

Some may argue that our selected design range/radius is insufficient for providing a worldwide deployment capability. Section VII, however, illustrates one of the consequences of providing too much range for the job at hand. There we show that, in a NATO reinforcement scenario in which fuel for the return trip is readily available in Europe, airplanes with a superior range capability could be less cost-effective than those with a lesser range capabiltiy. This occurs because the volume limits of the cargo compartment preclude a very long-range aircraft from taking off at or near maximum gross weight (see Fig. 4) when flying relatively short-range missions. That is,

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[a]A potential weakness of this argument is the vulnerability of Andersen AFB in a limited nuclear conflict. If Andersen is lost, the nearest appropriate airfield is Wake Island AFB (about 1300 n mi east of Guam) despite the presence of numerous smaller fields nearer Guam (e.g., Kobler in the Mariana Islands). The implications of Andersen's vulnerability are further discussed in Section VII.

they would be payload-volume limited rather than payload-weight limited. Note also that ranges in excess of 6000 n mi are generally inconsistent with the needs of commercial air freight operations and hence might preclude the use of the airplane in that role.

Of course, the design range or radius has little meaning for a nuclear-powered airplane. For these, the corresponding requirement is that the airplane carry sufficient JP (used for takeoffs and landings, see Section IV) to fly a radius mission profile (of unspecified distance) with the design payload.

Design Payload

There are no clear-cut criteria for the selection of a design payload. For a given design radius, the maximum gross weight of an airplane is principally determined by the design payload. A given airlift capacity can be achieved either with a large number of small airplanes or with a fewer number of large airplanes (with larger design payload). From an operational viewpoint, it is difficult, if not impossible, to define the size requirement logically. Two operational considerations which might influence the choice of size are runway saturation in the delivery area and the airplane's vulnerability. Runway saturation would tend to favor large airplanes, but a major deployment is likely to include many Army units going into several airfields (both to avoid road saturation and to distribute forces within the theater), and so runway saturation may not be a problem. Attrition would favor small airplanes, but again, careful selection of routes to minimize attrition could alleviate vulnerability concerns.

Thus, there appears to be no rationale based on operational requirements for selecting a particular design payload.[a] Our approach,

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[a]Although straightforward operational considerations cannot readily define a desirable design payload, a rational argument could be provided by an appropriate systemic analysis. Such an analysis is described in Section X.

therefore, has been to select a design payload that yields a maximum gross weight commensurate with the historical rate of growth of aircraft size.

Figure 6 shows the historical trends in aircraft gross weights. Since the present concern is with airplanes that would become operational in the late 1980s or early 1990s, the anticipated maximum

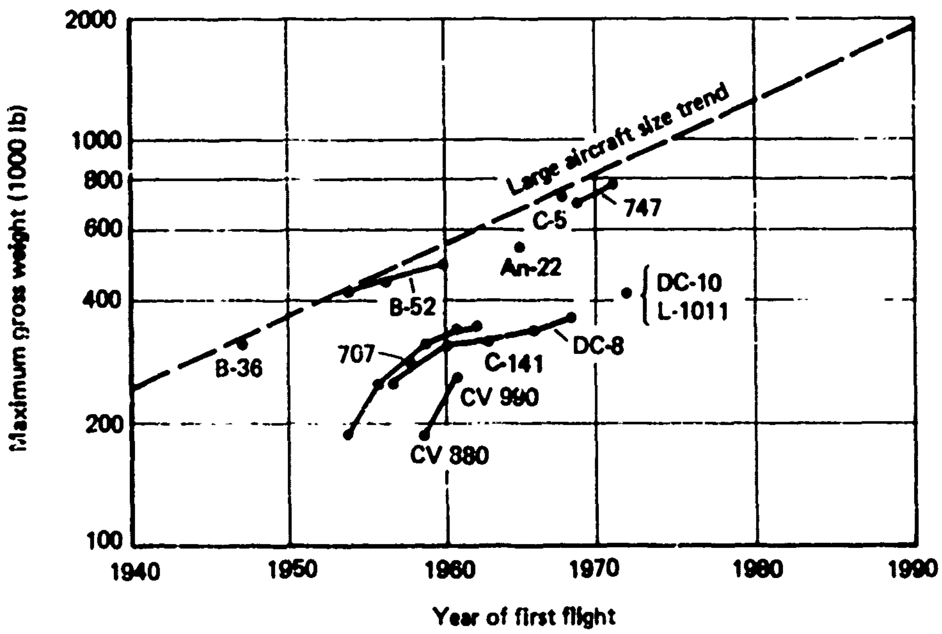

Fig. 6 — Historical trend in aircraft gross weight [25]

gross weight is in the 1.5 to 2.0 million lb range. A preliminary analysis indicated that a JP-fueled airplane in this gross weight range could deliver a 300,000 to 400,000 lb payload on the design radius mission.

An additional consideration in the determination is that the design payload should be some integer multiple of the heaviest item that must be airlifted in substantial quantity. The M-60 main battle tank is the most likely candidate and versions of this tank have

curb weights between 104,000 and 115,000 lb [26]. *We have therefore selected a design payload of 350,000 lb*; this should be sufficient to accommodate three tanks.[a]

The selected design point (350,000 lb for a 3600 n mi radius mission) will, of course, yield a different gross weight when fuels other than JP (e.g., liquid hydrogen) are considered. In Section IV, our circumvention of this difficulty is described in detail. Here we will simply state that we considered excursion-case designs that maintain the same design range but vary the design payload to yield maximum gross weights corresponding to the desired goal. Thus, potential biases against any of the alternative fuels are avoided.

Figure 4 illustrates another complication that arises when alternative fuels are considered. Earlier we noted that our design point falls between the X-point and the Y-point. The Y-point can be determined by the maximum fuel capacity of the airplane. For a JP-fueled airplane, this maximum is usually considered to be the integral fuel capacity of the wing. In our work, the X-point is determined by requiring that the airplane deliver its *maximum payload* on a 3600 n mi *range* mission. We think this appropriate because of the clearly defined requirements for NATO reinforcement.

With our approach, however, the maximum payload (i.e., the X-point) is dependent on the fuel alternative being considered. For example, the maximum payload (on a 3600 n mi range mission) will be substantially larger for a JP-fueled airplane than for one using liquid hydrogen--even though both airplanes satisfy the same design point. Section IV contains additional details on this phenomenon.

Cargo Compartment Dimensions

To assure convenient loading characteristics. the airplane's cargo compartment should have a rectangular planform. The compartment can thus be fully specified in terms of the cross-sectional shape and length of the cargo compartment.

[a]At best, the XM-1--the potential replacement for the M-60--is expected to be only modestly lighter.

Cargo Compartment Cross Section. We have already noted that the cargo compartment must be compatible both with outsized equipment and with containerized or palletized cargo. The outsized requirement determines the minimum acceptable height of the compartment. We have used the palletized/containerized cargo requirements to identify the desirable width dimension. In addition, the width should be commensurate with the dimensions of the most common oversize equipment, such as 2-1/2- or 5-ton trucks.

The standard military/commercial 463L pallet has a base 88 in. by 108 in. and a height normally of 8 ft or less. Air/surface intermodal containers vary in length from 10 ft to 80 ft but have a uniform cross section of 8 ft by 8 ft [27]. Sea/land containers (also 8 ft by 8 ft) could possibly be airlifted but would, at the least, require a flat-bottomed pallet, and this would add perhaps 6 in. to the height.[a] Army trucks and jeeps also have width dimensions approximately consistent with the 8-ft containers. In consequence, a floor width sufficient for three-abreast placement of 8-ft-wide loads would appear to be appropriate for our purposes.

The height dimension of the cargo compartment is somewhat more difficult to define. The C-5A ceiling height at the centerline is 13.5 ft and this height is maintained for a width of 13 ft [4]. These dimensions are the minimums for the Army's Armored Vehicle-Launched Bridge [28]. Our rather cursory analysis of Army equipment to be air-transported has failed to identify a greater height requirement than that for the bridge launcher. Thus, the minimum height dimension at the centerline appears to be 13.5 ft.

Most of the items that have a height dimension exceeding 9 ft are quite heavy (e.g., the main battle tank, or the bridge launcher); loads made up of such equipment invariably exceed the weight limits of the airplane rather than its volume limits. Thus, it is not necessary to maintain the 13.5 ft height over the entire width of the cargo compartment. A sidewall height of 10 ft should be adequate to accommodate

[a]Air/surface intermodal containers differ from the standard sea/land container in that they must have extra provisions for air transport such as a flat bottom, special indents for locking, higher strength walls, and decompression panels [27].

those items which can be loaded three-abreast. (Corresponding sidewall heights are 9.5 ft for the C-5A and 9 ft for the C-141A.)

The resulting minimum acceptable cargo-compartment cross section is detailed in Fig. 7. Examples of compatibility with constraining types of loads are also displayed. (Note that the cross sections of the refined conceptual designs are somewhat larger than the minimums developed in the preceding paragraphs; see Appendix A for an explanation of this.) The dimensions shown in Fig. 7 should be regarded as approximate.[a] A final resolution of these dimensions requires detailed analyses of clearance requirements, etc., that have not been fully examined in the present work.

Cargo Compartment Length. Specifying a desirable cargo floor length is also a complex and somewhat arbitrary task. Ideally, the floor area should be compatible with the types of loads envisioned, but it is virtually impossible to achieve such compatibility when deploying Army unit equipment. For example, the M-60A1 tank has an average floor loading of more than 375 lb per square ft [26]. At the other extreme, the average floor loading of an Army airmobile division is only about 22 lb per square ft [3]. Given such divergent requirements, an attractive compromise is not readily apparent.

Our solution has been to make the floor area (i.e., floor length, since the width has already been specified) compatible with palletized loads. The 350,000-lb design payload corresponds to 76 military/commercial 463L pallets with an average load of 4600 lb--this is the average peacetime pallet load, including tare weights, of pallets passing through Travis AFB (Calif.). The pallet arrangement shown in Fig. 7(a) yields a minimum floor length of 220 ft to accommodate the 76 pallets.

For purposes of comparison, the C-5A has a maximum capacity of 36 of the 463L pallets [3]. Similarly, the maximum available internal

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[a]For example, the Douglas Aircraft Company has suggested that the minimum floor width for loading three air/surface intermodal containers abreast is 302 in. [29]. Our design analysis would clearly not be sensitive to differences such as this (i.e., the difference between 302 in. and 300 in., as shown in Fig. 7(a)).

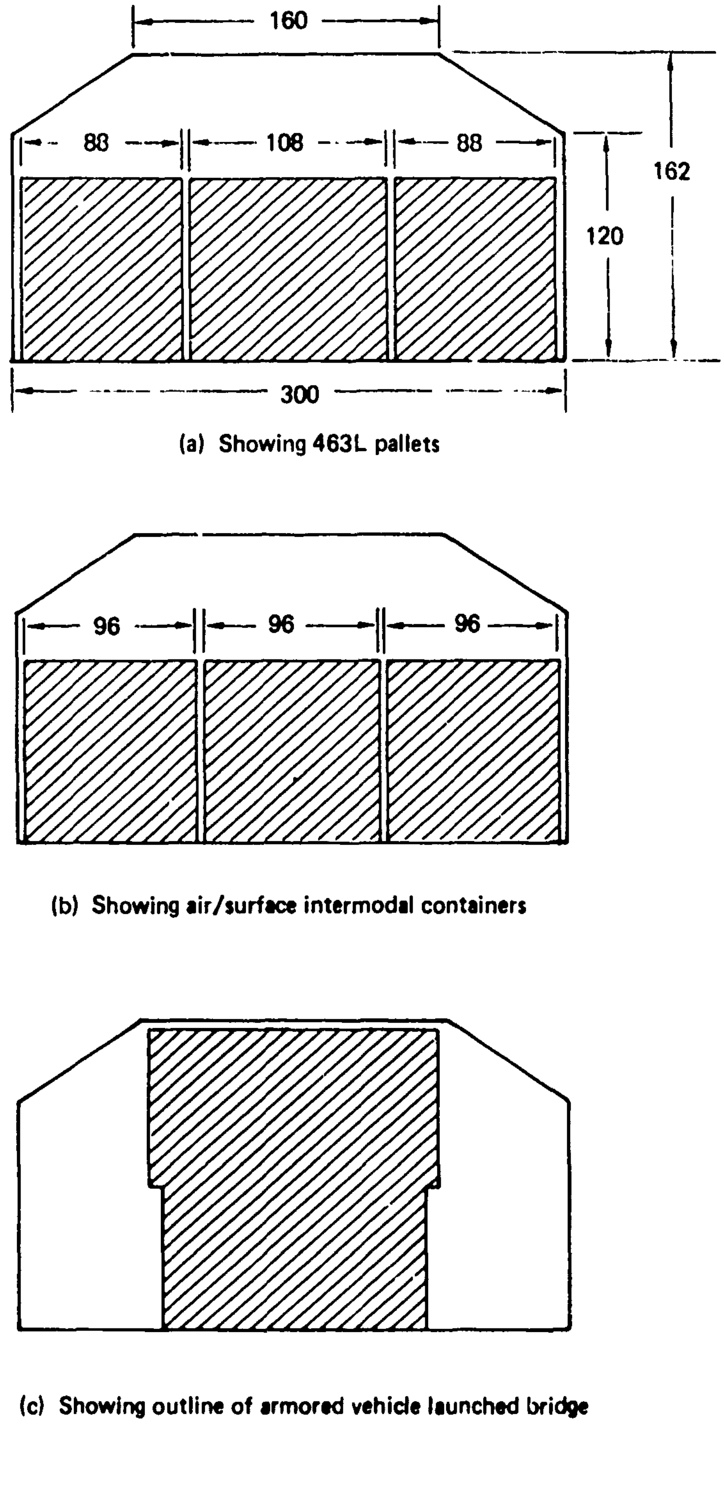

Fig. 7 — Suggested minimum acceptable cargo-compartment cross section (NOTE: All dimensions are in inches.)

volume for the just-described configuration when loaded with air/surface intermodal containers is 35,350 cubic ft compared to 17,800 cubic ft for the main deck of the 747-200F [30].

Cruise Conditions

Here the principal parameters of interest are the average cruise speed (or cruise Mach number) and the initial cruise altitude. Specifying the latter is straightforward. The obvious need to avoid adverse en route weather implies a minimum initial cruise altitude of 30,000 ft.

The cruise Mach number is a more subtle issue. Heretofore, the cruise speed of a subsonic transport was invariably consistent with the maximum for the then current "state-of-the-art" high-speed wing design. A desire to increase productivity has increased the state of the art to cruise Mach numbers approaching 0.9. In an era of fuel shortages and increasing fuel prices, however, such a high speed goal may be less desirable.

For the present application, we suggest a cruise Mach number in the range of 0.75 to 0.80. Recent studies have shown that cruise speeds greater than 0.80 substantially increase mission fuel consumption and costs--and the effects are greater the further the transonic drag-rise regime is penetrated. On the other hand, a cruise Mach number less than 0.75, given today's supercritical airfoil technology, appears to offer little potential for additional reductions in mission fuel consumption while causing a significant erosion of productivity [31].[a]

The choice of the cruise Mach number is also one of the more important parameters with respect to multimission considerations. Many of the missions we have discussed require the airplane to loiter for extended periods. We will expand on this point later in the section when we discuss the compromises for a multimission capability.

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[a]Of course, we are presuming that propulsive power is being supplied by high-by-pass-ratio turbofan engines. If turboprops (or propfans) are considered, somewhat different conclusions might emerge. Such considerations, however, were beyond the scope of the present investigation.

Airfield Considerations

An implicit assumption of our work is that the very large airplanes will be compatible with existing runways. Parameters to be specified include takeoff and landing distances and runway-bearing characteristics; these, of course, should also be compatible with operational objectives.

Table 1 shows the distribution of U.S. airfields by runway length. Very large airplanes, when performing in the strategic airlift role,

Table 1

NUMBER OF AIRFIELDS WITH HARD SURFACE RUNWAYS EQUAL TO OR GREATER THAN THE LISTED DISTANCE [32]
(As of July 1967)

Runway Distance (ft)	Continental U.S.		Alaska and Hawaii		Total Airfields
	Civil	Military	Civil	Military	
4000	1230	253	33	17	1533
5000	801	235	25	13	1074
6000	350	199	15	12	576
7000	215	184	13	10	422
8000	126	170	8	8	310
9000	75	115	6	5	201
10000	36	90	4	3	133
11000	17	68	1	1	85
12000	8	44	1	1	53
13000	3	19	--	1	23
14000	1	2	--	1	4
15000	--	1	--	--	1

can generally be assumed to be operating out of the longer military or commercial fields. Other of the candidate missions, notably the strategic missile launcher, are enhanced if the airplanes can be dispersed to a large number of airfields. For this reason, we have selected

8000 ft as the takeoff critical field-length. Note that Table 1 shows that decreasing the field length from 9000 to 8000 ft increases the number of suitable airfields by about 50 percent.

The landing distance (over a 50-ft obstacle) is also a subtle issue. For this, the requirements of the strategic airlift mission dominate, since the ability to deploy to as many airfields as practical is desirable. An appropriate landing distance that does not overly constrain the airplane's design can be derived on the basis of two landing conditions of particular interest.

1. The airplane flies a 3600 n mi mission and lands with reserve fuel and either the maximum payload or the design payload plus sufficient fuel for the return leg. (Note that the landing weight is the same in either case.)
2. The airplane flies the maximum range mission and lands with reserve fuel and the design payload.

Because the takeoff characteristics at any gross weight are known (since the critical field-length requirement essentially defines them), the takeoff distances (after offloading the payload) implied by both of the above conditions are also known. Logically, then, those distances become the minimum landing distances for conditions (1) and (2), respectively.

Alternatively, a landing distance less than about 6000 ft implies a capability that might be but infrequently useful to a strategic airlifter (see Table 1, for example). Therefore, we suggest a design landing distance of 6000 ft (on the design radius mission) or the distance derived as described above--whichever is greater. For design purposes, moderately adverse runway-surface conditions (i.e., wet concrete) seem appropriate.

Finally, in order to ensure compatibility with most of the 8000-ft and longer hard-surface runways, the landing gear footprint pressure should be comparable to a 200,000-lb-class commercial aircraft.

Such a runway bearing constraint appears to be attainable--even without recourse to advanced technologies such as air-cushion landing systems.

COMPROMISES FOR MULTIMISSION CAPABILITY

The airplane characteristics specified thus far are generally compatible with our multimission requirements. To be able to perform all of the missions described earlier, the airplane must have a tanker capability and be capable of air-launching a variety of vehicles. Furthermore, since many of the missions required a substantial loiter time on-station, the airplane must have good endurance characteristics; this latter requirement is one of the more significant multimission compromises.

Tanker Capability

Our suggested approach for providing a tanker capability is to include the essential permanent installations in the basic airplane design. When the airplane is to be operated as a tanker, the appropriate mission kit would be installed with relative simplicity. The primary elements of the mission kit would be either a single refueling boom (or three booms for the in-flight refueling of fighters) plus associated equipment. The weight penalty for the suggested approach will be approximately one percent. That is, the empty weight of the airplane itself with its basic tanker installations (but not the mission kit) will be about one percent greater than an airplane configured solely as a strategic airlifter [4].

If necessary, the basic installation can include underfloor fuel tanks so that the maximum gross weight can be realized when the airplane is performing as a tanker. (Referring to our earlier discussion of range-payload trade-offs, this implies that the Y-point will correspond to a zero payload for the JP-fueled airplane. The cryogenic-fueled airplanes, whose design points correspond to the Y-point, should have provisions for the installation of additional cryogenic fuel tanks in the cargo hold.)

Air-Launch Capability

At least three approaches can be envisioned for providing an air-launch capability. These are:

1. A rear-loading door can be incorporated into the design of the strategic airlifter in a fashion similar to that of the C-5A. Vehicles ranging in size from RPVs to ICBMs could then be air-launched [33].
2. Those aircraft which require an air-launch capability could be modified with a side-opening door similar to that suggested by Boeing for its 747 aircraft [34].
3. The air-launch-capable aircraft could have basic structural differences from the airlifter/tankers that would give them the ability to air-launch through what would appear to be large bomb-bay doors [35].

Although we have not examined these alternatives in detail, we believe the first concept is the most appropriate. The second may preclude the air-launching of large vehicles such as ICBMs. Employment of the third concept would reduce the ability of individual airframes to serve in various mission roles.

In summary, the basic airlifter should be designed with a front- and rear-loading capability. The characteristics of the aft door should be such that air-launching (at relatively low speeds) of small as well as large vehicles is possible.

Endurance Characteristics

Many of the missions include a substantial loiter time at some distance from the originating airfield. Such a requirement generally conflicts with the design characteristics of a strategic airlifter. Transport aircraft are configured for efficient cruise at high subsonic Mach numbers, something normally achieved by sweeping the wings and flying at speeds below, but near, the beginning of the transonic drag rise. Loiter-type aircraft, on the other hand, are designed in

glider fashion for maximum endurance at minimum fuel consumption. This normally implies large-span, unswept wings, and relatively low subsonic Mach numbers. (See also the discussion in Appendix C.)

The following trade-off must therefore be considered: an airplane designed for maximum range, flying a maximum-endurance mission versus an airplane designed for maximum endurance, flying a maximum-range mission. Our initial evaluation of this trade-off suggests that the percentage loss in productivity is greater for the maximum-endurance airplane flying a transport-type mission than is the percentage loss in endurance for a transport aircraft flying a loiter-type mission.[a] Our conclusions are, therefore, that the compromises necessary for a multimission aircraft should be weighted in favor of the airlift mission, and that the airplane should be designed primarily for maximum range, but with a continuing awareness of a possible need to operate so as to maximize its endurance characteristics.

The foreseeable technology for the time frame of interest suggests that a cruise Mach number between 0.75 and 0.80 is appropriate. Incorporation of advanced supercritical airfoil technology should permit the design of a moderately thick, minimum-sweep wing (i.e., just enough sweep to enhance stability).

Three additional considerations strengthen this conclusion. First, a recent Boeing study of commercial transport airplanes has indicated that only modest reductions in fuel consumption and even smaller reductions in direct operating costs can be realized by reducing the cruise Mach number below 0.8. On the other hand, it indicated that increasing the cruise Mach number beyond 0.8 substantially increased fuel consumption as well as costs [31].

The second consideration is related to air-traffic control. Introducing into the system an airplane with a lower cruise speed than other airplanes would significantly increase traffic management problems on heavily traveled routes. Although perhaps of lesser concern

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[a]In this evaluation, we are comparing airplanes of equal gross weights and design payloads.

for a military transport, such a complication would certainly affect the utility of the airplane as a commercial freighter.

Finally, some of the station-keeping mission profiles described earlier can include a significant cruise phase--from the air base to the station-keeping point. A lower cruise speed would consequently result in the airplane spending a smaller fraction of the available operational time on-station. (For example, see the discussion in Section VIII.)

SUMMARY

Table 2 summarizes the desired airplane characteristics. In addition to the parameters shown, the airplane must include

Table 2

MINIMUM REQUIRED VLA PERFORMANCE CHARACTERISTICS

Characteristics	Suggested Value
Design radius	3,600 n mi[a]
Design payload	350,000 lb[a]
Cargo compartment	
Maximum width	25 ft
Maximum height	13.5 ft[b]
Length	220 ft
Cruise Mach number	0.75 to 0.80[c]
Initial cruise altitude	30,000 ft
Takeoff critical field length[d]	8,000 ft

[a]Maximum payload to be carried on 3600 n mi range mission, 2.25 g limit load factor.

[b]Maximum height for a width of at least 160 in.

[c]To be consistent with state-of-the-art airfoil technology yielding minimum-sweep wings.

[d]Landing field length to be consistent with takeoff characteristics for return leg of design point missions or 6000 ft--whichever is greater.

provisions for the rapid installation of a three-boom tanker-mission kit and must be able to air-launch vehicles as large as a 100,000-lb ICBM. This latter requirement probably implies the need for a rear-loading capability.

Note that the design point is specified at a limit load factor of 2.25 g. As such, it corresponds to a wartime capability. In peacetime (or in commercial use), the airplanes would generally be restricted to lower gross weights corresponding to a 2.50 g load factor (see Appendix A).

III. SCREENING OF ALTERNATIVE FUELS

This section describes the screening process employed to identify the most promising chemical fuels for future Air Force use. The fuels that survived the screening were then subjected to a more detailed analysis, described in [19].

The screening consisted of two phases. In the first, the physical characteristics of fuels potentially available were examined and, based on these characteristics, a list was compiled of promising candidate fuels. Then, this list of candidates was further reduced by developing conceptual airplane designs for each of the fuels; these results were used to select the most promising alternatives. Both phases are discussed in this section.

CANDIDATE FUELS (FIRST SCREENING)

In recent years, many synthetic fuels[a] have been suggested for application in transportation systems. We have reviewed the existing literature to identify candidate synthetic fuels which might be available for aircraft propulsion. Table 3 lists these chemical fuels along with some of their important physical properties.

Based largely on these physical characteristics, we selected the following potentially promising candidates:

- o Liquid hydrogen (LH_2)
- o Liquid methane (LCH_4)
- o Conventional jet fuel (JP)[b]

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[a]We define a synthetic fuel as one that can be derived from a primary energy resource other than crude oil or natural gas.

[b]Henceforth, we do not distinguish between JP-4 and JP-8. As shown in Table 3, the physical characteristics of the two are so nearly identical that their relative impacts on *conceptual* airplane design are essentially unnoticeable. In actual practice, of course, there are considerable differences between the two fuels. Today, the standard Air Force fuel is JP-4, but the USAF Scientific Advisory Board has recently recommended a conversion to JP-8. (JP-8 is similar to Jet-A, the standard commercial jet fuel.) Such a conversion should help relieve future JP supply problems as well as reduce combat vulnerability and improve crash survivability [42].

Table 3

PROPERTIES OF CANDIDATE FUELS

Fuel	Heat of Combustion[a]		Density (lb/ft^3)	Boiling Point (°F)	Autoignition Temperature in Air (°F)	Flammability Limits in Air (percent)
	Btu/lb	Btu/gal				
Acetylene (C_2H_2)	20,700	106,900	38.6	-119	635	2.5 to 80.0
Ammonia (NH_3)	8,000	45,600	42.6	- 28	1,204	15 to 27
Ethanol (C_2H_5OH)	11,600	76,600	49.4	173	---	3.3 to 19.0
Hydrazine (N_2H_4)	7,200	60,100	62.4	236	518	4.7 to 100
Jet fuel (JP-4) (Naphtha-like)	18,700	121,100	48.7	210	480	0.8 to 5.6
Jet fuel (JP-8) (Kerosene-like)	18,600	128,300	51.6	400	450	0.6 to 5.0
Liquid hydrogen (LH_2)	51,600	30,400	4.4	-423	1,085	4.0 to 74
Liquid methane (LCH_4)	21,500	74,400	25.9	-259	1,000	5.0 to 15
Methanol (CH_3OH)	8,600	58,100	50.5	149	867	6.7 to 37
Monomethylamine (CH_3NH_2)	13,500	76,700	42.5	45	306	5.0 to 21
Propane (C_3H_8)	19,900	97,100	36.5	- 44	---	2.1 to 9.4
Gasoline[b] (C_8H_{18})	19,100	111,800	43.8	257	---	1.1 to 7.0

SOURCE: Compiled from the open literature [36-39].

[a]Lower heating values.

[b]Included for reference only.

- Ethanol (C_2H_5OH)
- Methanol (CH_3OH)
- Ammonia (NH_3)

These fuels are listed in order of the decreasing magnitude of the fuel's gravimetric heat of combustion (Btu/lb) based on the lower heating value.

The Surviving Candidates

Liquid hydrogen, by virtue of its extremely high heat content per pound, is obviously interesting as a potential aircraft fuel. Indeed, many have suggested that LH_2 is the leading alternative to jet fuel refined from petroleum [38,40,41]. Table 3 shows its principal drawbacks: an exceedingly low volumetric heat of combustion and a very low boiling point, which makes necessary cryogenic storage.

Next to liquid hydrogen, liquid methane has the highest gravimetric heating value, and this is coupled with a substantially greater heat content per gallon and less severe cryogenic storage requirements. Furthermore, an extensive distribution network for gaseous methane is already in place (i.e., natural gas pipelines). As domestic natural gas supplies diminish, we believe that methane--probably synthesized from coal--is almost certain to be widely used as a substitute. Including LCH_4 in a list of potentially attractive fuels seems therefore appropriate.

A conventional jet fuel (JP) is listed next. Since we are interested in fuels that can be obtained from some resource other than petroleum, we must presume that this synthetic JP is derived from either coal or oil shale. Not to have included JP, given its preeminence as today's aircraft fuel, would have been ludicrous.

Methanol (wood alcohol) and ethanol (grain alcohol) are listed next. Note that both have relatively low heat contents per pound; however, both are liquids at standard conditions of temperature and pressure and would thus more conveniently conform to existing aviation-fuel distribution and storage systems. Both fuels are relatively easy

to synthesize, with ethanol having the additional potential advantage of being easily obtainable from the biomass (e.g., agricultural products). We felt that both should be included in our initial list of alternatives despite their relatively unattractive heats of combustion.

The last potentially attractive alternative fuel is ammonia. Despite a low heat content per pound, ammonia has the singular advantage of having the highest gravimetric heat of combustion of any non-carbonaceous fuel except liquid hydrogen. Thus, ammonia does not require a hydrocarbon resource for its synthesis and can also be stored at ambient temperatures under modest pressure.

The Discarded Fuels

The remaining four candidate fuels shown in Table 3 were discarded from further consideration for a number of reasons. Consider first hydrazine, which has heats of combustion that are comparable to methanol or ammonia. The only apparent reasons for pursuing hydrazine would be its significantly higher boiling point when compared to ammonia or, perhaps, its greater flammability limits. However, using the best available synthesis technology would result in unit energy costs at least of an order-of-magnitude greater than that for ammonia. Furthermore, the successful development of an advanced process would, at best, yield unit prices comparable to ammonia [36]. In light of this, there is little reason for further pursuing hydrazine as an aircraft fuel.

Monomethylamine is of interest because its heats of combustion lie midway between the alcohols and conventional jet fuels and because it can be nominally handled as a liquid. In actual practice a mixture of 50 percent monomethylamine, 20 percent dimethylamine, and 30 percent trimethylamine would probably be employed; the average heating value of the mixture would be about 15,100 Btu/lb. The methylamines are formed by the gas-phase condensation of methanol and ammonia, and its synthesis would thus include *both* methanol and ammonia manufacturing facilities [37]. We anticipate that the average unit energy costs for the mixed methylamines would be significantly greater

than for either methanol or ammonia. (Note also that a carbon source is required to synthesize the methanol, so there is no advantage in that regard.) Given the relatively complex synthesis process, the average unit energy costs for the mixed methylamine should be, at best, only modestly less than the cost of JP synthesized from coal. Thus, the mixed methylamines showed little promise of being a viable alternative, and we therefore eliminated them from further consideration.

Acetylene and propane have somewhat attractive physical characteristics, but we were unable to identify any synthesis processes for manufacturing either of these relatively complex hydrocarbons that could result in a lower unit energy cost than that projected for conventional jet fuel made from coal or oil shale. Since their gross characteristics are quite similar to JP, we believed that it would be superfluous to consider them further.

FURTHER SCREENING OF THE CANDIDATE FUELS

The candidate chemical fuels were subjected to a finer-grained screening in order to reduce the number of alternatives under consideration in our more detailed analysis. The screening approach used was to develop rough conceptual airplane designs corresponding to the requirements described in Section II; fuel alternatives that implied obviously inferior aircraft were then discarded. The maximum gross weight of the airplane was used as the figure-of-merit.

The conceptual designs were developed by utilizing a modified version of an existing Rand transport airplane design model.[a] The principal modifications, of course, were those that permitted the analysis of fuels other than JP.

The resulting airplane gross weight as a function of the design radius is presented in Fig. 8 for three of the candidate fuels. In all cases, the design payload is assumed to be 350,000 lb. For the target design radius of 3600 n mi, the resulting gross weights are

[a] The transport airplane design model was originally developed by Thomas F. Kirkwood of Rand.

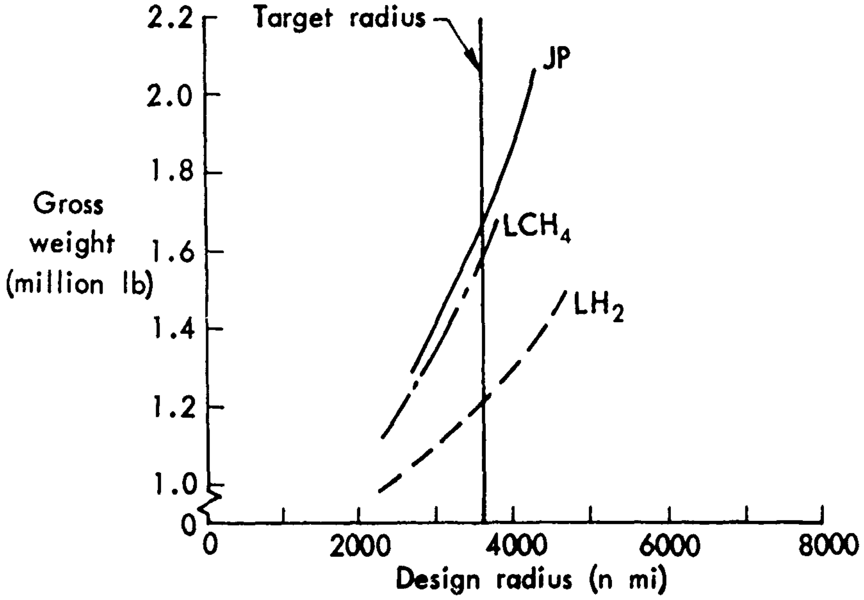

Fig. 8—Gross weight of airplanes using alternative fuels in terms of design radius

about 1.68 million lb for JP, 1.59 million for LCH_4, and 1.22 million for LH_2. Gross weights of this magnitude are expected to be within the state of the art in the 1985 to 1995 time frame (see Fig. 6).[a]

Similar results for ammonia, methanol, and ethanol are presented in Fig. 9. *Note that Fig. 9 shows the resulting gross weights as a function of design range; the target radius has thus been replaced by a target range of the same magnitude.* Our reasoning here becomes

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[a]The results shown in Fig. 8 (and Fig. 9) should be interpreted as only rough approximations. For example, the takeoff field-length requirements cited earlier are not included as a design constraint. In spite of such simplifications, these results are adequate for present purposes. Results of the more refined and detailed design analysis for the most promising alternative fuels are contained in Section IV.

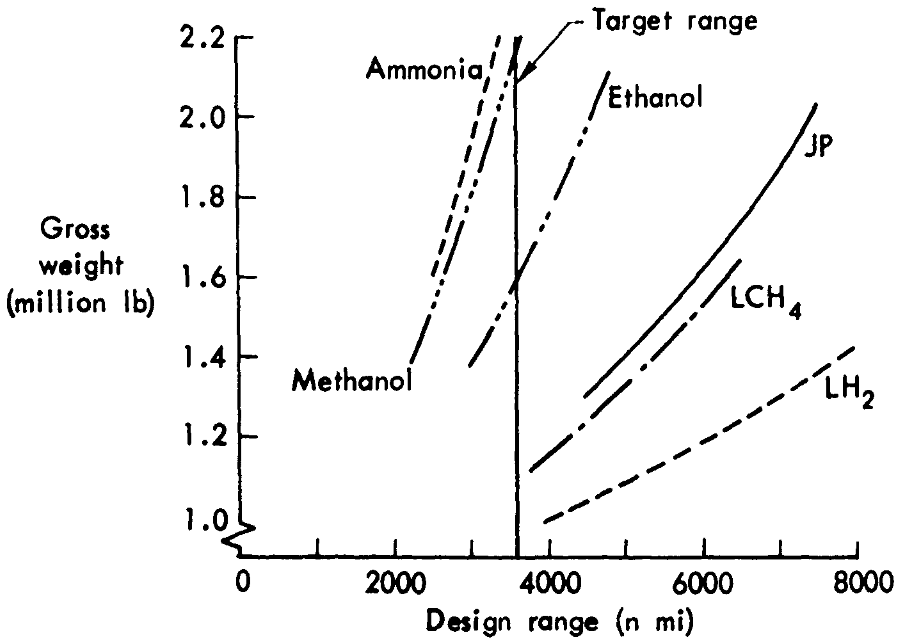

Fig. 9—Gross weight of airplanes using alternative fuels in terms of design range

apparent when the results for the alcohols and ammonia alternatives are contrasted with the comparable JP, LCH_4, or LH_2 results, also depicted in Fig. 9. Note that for gross weights between 1.5 and 2.5 million lb, the alcohols and ammonia have *range* capabilities that are on the same order as the *radius* results for the other fuels. Stated another way, for an alcohol- or ammonia-fueled airplane to have a range/radius capability similar to that of the JP, LCH_4, or LH_2 alternatives it would require a maximum gross weight well in excess of 2.5 million lb.

THE MOST PROMISING ALTERNATIVE FUELS

The results presented in Figs. 8 and 9 clearly indicate that conventional jet fuel, liquid methane, and liquid hydrogen are the

only viable chemical-fuel alternatives. Although our screening analysis is based on their use in very large airplanes, we believe that this conclusion is generally extensible to all classes of military airplanes.

A fourth alternative, nuclear propulsion, may only be examined in the context of very large airplanes. Including nuclear propulsion in the rough screening would have been inappropriate because of the unique characteristics of nuclear-powered airplanes. Specifically, for a given gross weight and payload, the airplane would have essentially an unlimited range or radius capability. Such a unique capability clearly merits attention.

Recent system studies of nuclear-powered aircraft indicate that the desired design payload of 350,000 lb would require an airplane with a gross weight on the order of two million pounds [10,25]. Such a gross weight is commensurate with the results for the most promising chemical fuels. (Included in the nuclear airplane gross weight is sufficient fuel for takeoff and landing using conventional JP. Since the present design point is a radius mission, sufficient chemical fuel for two takeoff-landing cycles is required. This aspect of the nuclear-powered airplane is more thoroughly discussed in Section IV and Appendixes A and B.)

IV. CHARACTERISTICS OF THE ALTERNATIVE AIRPLANES

This section describes the characteristics of the alternative airplanes that were evaluated. We first discuss the reasons that each of the alternatives was selected for detailed examination. Important aspects of the design and performance of each alternative are then presented.

ALTERNATIVES CONSIDERED

We made detailed evaluations of seven alternative airplanes. The design of four of them corresponds to the design constraints suggested in Section II; each of the four employs one of the fuels that survived the screening described in Section III. The maximum gross weights of these design-point airplanes are presented in Table 4. Note that the maximum gross weight of the VLA-JP and VLA-LCH_4 aircraft are within the stated goal of 1.5 to 2.0 million lb.[a] However, the VLA-LH_2's gross weight is somewhat less than the goal and the VLA-NUC's significantly greater.

Table 4

DESIGN-POINT VERY LARGE AIRPLANES

Designation	Maximum Gross Weight (lb)
VLA-JP	1,839,000
VLA-LCH_4	1,864,000
VLA-LH_2	1,275,000
VLA-NUC	[illegible],660,000

[a]Throughout this report, the very large airplanes (VLAs) are identified by the fuel employed--JP for conventional jet fuel, LCH_4 for liquid methane, LH_2 for liquid hydrogen, and NUC for nuclear propulsion.

If the state of the art that a particular airplane reflects can indeed be represented by its maximum gross weight, the VLA-LH_2 design implies a lower technological level than that embodied in the VLA-JP.[a] Similarly, the VLA-NUC would represent a significant advance in technology, even if the new-technology aspects of nuclear propulsion are discounted. Therefore, the possibility at least exists that comparisons of the VLA-JP with either the VLA-LH_2 or the VLA-NUC could be biased since each airplane represents a different level of technology.[b]

We have eliminated this dilemma by including in our analysis two excursion-case airplanes. The maximum gross weights of these airplanes--designated VLA-LH_2* and VLA-NUC*--are shown in Table 5. Note that both are within the gross-weight range of our original goal.

Table 5

EXCURSION-CASE VERY LARGE AIRPLANES

Designation	Maximum Gross Weight (lb)
VLA-LH_2*	1,622,000
VLA-NUC*	1,940,000

[a] In Section II, we intimated that maximum gross weight was, in fact, an appropriate measure of the state of the art. This is in substantial agreement with Cleveland's classic paper on size effects in airplane design--at least for conventional airplanes [23].

[b] We would be less concerned if our analytical capability for predicting costs and performance for such airplanes were precise. Ultimately, however, such analysis is largely formulated on extrapolations made from the data base composed of existing airplanes. The observation that the difference in the gross weights of the VLA-NUC and VLA-LH_2 aircraft (about 1.4 million lb) is almost twice the maximum gross weight of the largest existing airplane should give one pause.

To enhance the comparison of the alternative very large airplanes and to provide a meaningful benchmark, we have included a contemporary airplane as a seventh alternative. For this purpose, we selected a new production version of the C-5A that the Lockheed-Georgia Co. recently proposed and designated the C-5B. One of the least complex of the proposed derivatives of the C-5A, this C-5B model does not include the C-5A items required for tactical airlift operations and has been modified to provide an aerial tanker capability. The maximum gross takeoff weight of the C-5B is 769,000 lb.[a]

DESCRIPTION OF THE AIRPLANE DESIGNS

The seven alternative airplanes will be described in terms of their general design characteristics and their performance attributes. The design aspects include

- Weights
- Physical characteristics (dimension, etc.)
- Aerodynamic and propulsion parameters

Performance characteristics illustrated are

- Payload capability (as a function of range)
- Fuel off-load capability

[a]Of course, modified versions of other contemporary airplanes, such as the Boeing 747 or Douglas DC-10, might have been included in the analysis, but resource limitations prevented our doing so in the present study. There are several reasons for our choosing the C-5B: (1) the detailed characteristics of the airplane were readily available, (2) the C-5B has loading and basing characteristics similar to very large airplane requirements, and (3) only the C-5 has demonstrated an air-launch capability. Our using the C-5B as an alternative, however, is not meant to suggest that it would be more attractive in the various mission applications than modified versions of either the 747 or the DC-10.

- o Range/radius with aerial refueling
- o Endurance capability

We describe these alternative airplanes in order to provide the reader with insights into their different attributes. The importance of these differences will become apparent in the discussion of the mission analyses.

(See Appendix A for a detailed discussion of the ASD's design analysis of the VLA alternatives. Appendix B provides comparable information on the propulsion system designs. Additional definition of the proposed C-5B is included as part of Appendix C.)

General Design Characteristics

Table 6 summarizes the weight characteristics of the alternatives under consideration.[a] Observe the wide variation in empty weights of the VLAs. For the VLA-NUC aircraft, about 650,000 lb of the empty weight can be attributed to the nuclear reactor and its containment vessel. If these weights are netted out, however, the empty weight of the VLA-NUC is still more than 465,000 lb greater than that of the VLA-JP. The reactor system in the VLA-NUC* weighs approximately 530,000 lb. Note also that the empty weight of the VLA-LH_2 alternative is about 11 percent less than that of the VLA-JP, and the empty weights of both the VLA-LCH_4 and the VLA-LH_2* are about 15 percent more.

Interestingly, the empty-weight fraction (i.e., empty weight divided by maximum gross weight) is 0.43 for the VLA-JP compared to 0.46 for the C-5B. According to Cleveland, such a trend in empty-weight fraction would be well within the expected state of the art [23].

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[a]Unless otherwise noted, all weight and performance characteristics cited in this report correspond to flight at a limit load factor of 2.25 g. In normal peacetime operation, aircraft of this type are generally restricted to load factors of 2.50 g; the lower figure is, however, usually used for wartime or for emergency planning. Weights and performance at 2.50 g are noted in Appendix A.

Table 6

WEIGHT CHARACTERISTICS OF THE ALTERNATIVE AIRPLANES
(Thousands of pounds)

Weights	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Empty weight	356	782	861	696	1900	898	1404
Operating empty weight[a]	362	794	872	704	1907	910	1409
Design payload[b]	216	350	350	350	350	425	230
Maximum payload	237[c]	550[c]	550[c]	550[c]	480[d]	550[c]	325[d]
Maximum fuel weight[a]	407	861	642	221	404[e]	362	301[e]
Maximum gross weight[f]	769	1839	1864	1275	2660	1622	1940

[a]Cargo mission configuration.

[b]Payload capability on a 3600 n mi radius mission for the VLA alternatives; the C-5B's range is 2730 n mi with the stated design payload (see Appendix C).

[c]Fuselage and/or wing structural limitation (2.25 g).

[d]For range mission, limited by maximum gross weight.

[e]JP for takeoffs, landings, and emergency operation.

[f]Limit load factor of 2.25 g.

[g]Ground-maneuver limit at 2.25 g; see Appendix C.

The design payload for the design-point VLAs is, of course, identical and is more than 60 percent greater than that of the C-5B. The design payload of excursion-case VLAs has been adjusted to yield the desired maximum gross weights.

The basis for the maximum payloads of the VLAs shown in Table 6 deviates somewhat from the suggested approach outlined in Section II.[a] An early design iteration on the JP-fueled alternative indicated that an airplane designed to carry a 350,000-lb payload on a 3600 n mi radius mission would inherently have the capability to carry 550,000 lb on a 3600 n mi range mission. To simplify the detailed design analysis, the maximum payload of the chemical-fueled VLAs was set a priori at 550,000 lb. As we will see, neither liquid-hydrogen-fueled airplane can carry this payload on a 3600 n mi range mission, but we believe the implications of this deviation for deriving maximum payload is inconsequential to the outcome of the analysis.

The maximum payload for the nuclear-powered airplanes is determined in another way. The VLA-NUC can deliver its design payload on a radius mission of essentially unlimited distance. Maximum payload, however, corresponds to the payload that can be carried on a range mission. Thus, for the VLA-NUC, the approximately 130,000 lb of JP required for the zero-payload return leg on a radius mission can be replaced by useful payload on a range mission.

Note also the very substantial quantities of JP that are required by both nuclear airplanes as a consequence of the design constraints imposed in this study. These require that the reactor be shut down during takeoffs and landings; furthermore, JP must be carried to provide an 850 n mi cruise in the event of an emergency shutdown of the reactor during the cruise phase of the flight.[b] The former constraint is included for reasons of safety, the latter to minimize the possibility

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[a]Recall that we suggested the maximum payload of the chemical-fueled VLAs should correspond to a 3600 n mi range mission.

[b]When flying radius missions with the design payload, both nuclear-powered airplanes are capable of a 1250 n mi emergency cruise during the outbound mission leg.

of losing a very expensive weapon system in a perhaps much-less-than catastrophic failure of the reactor system. Clearly, these design constraints greatly influence the nuclear airplane's configurations. However, the constraints appear wholly appropriate for our present purposes.[a] (See also the discussion in Appendix A.)

Some of the important physical characteristics of the alternative airplanes are presented in Table 7. As shown, the aerodynamic aspect ratio of the VLA alternatives is only slightly greater than that of the C-5B. Note also that the maximum wing loading of the chemical-fueled VLAs is about 130 lb per sq ft compared to 124 for the C-5B. The nuclear airplanes are only modestly lower, at 116 lb per sq ft. (Profiles, planforms, and fuselage cross section for each of the VLA alternatives are included in Appendix A.)

Table 8 summarizes some of the aerodynamic and propulsion system characteristics of the alternatives. The smaller zero-lift drag coefficient of the VLA-JP compared to the C-5B is largely a consequence of the proportionately reduced drag contribution of the VLA-JP's fuselage. This translates into a somewhat higher maximum lift-to-drag ratio. Observe that both LH_2-fueled airplanes exhibit greater zero-lift drag coefficients than the VLA-JP, because the fuselages (which contain the cryogenic storage tanks) have a larger surface area. Both liquid-hydrogen-fueled VLAs suffer a corresponding reduction in maximum lift-to-drag ratio. The nuclear airplanes, on the other hand, show a smaller zero-lift drag coefficient since their higher gross weights require a larger wing area while the size of of their fuselages is similar to that of the VLA-JP.

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[a]Different operational concepts could modify these design constraints. For example, if the nuclear airplane were not permitted to overfly any land mass (even with the reactor shut down), then takeoffs and landings from coastal bases could possibly be made under nuclear power with probably some chemical-fueled assistance. The next logical step is to consider a seaplane; in this case the 850 n mi recovery range is no longer required since the airplane can simply sit down in case of a reactor emergency. However, our primary mission is strategic airlift, and the above concepts would greatly reduce the utility of the nuclear-powered airplane in the airlift role. We will, however, discuss these issues further in the section describing the station-keeping mission analyses.

Table 7

PHYSICAL CHARACTERISTICS OF THE ALTERNATIVE AIRPLANES

Physical Characteristic	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Wing Geometry							
Area (ft^2)	6,200	14,250	14,250	9,808	23,016	12,477	16,786
Aspect ratio	7.75	8.06	8.06	8.10	8.07	8.10	8.06
Span (ft)	223	339	339	282	431	318	368
Wing loading (lb/ft^2)	124	129	131	130	116	130	116
Fuselage Length (ft)	234	330	330	373	350	417	254
Cargo Compartment							
Length (ft)	121[a]	220	220	220	220[b]	264	124[b]
Width (ft)	19	25	25	25	25	25	25
Maximum height (ft)	13.5	13.5	13.5	13.5	13.5	13.5	13.5

[a] 145 ft, including ramps.

[b] In two equal-length compartments.

Table 8

AERODYNAMIC AND PROPULSION PARAMETERS FOR THE ALTERNATIVE AIRPLANES

Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC[a]	VLA-LH_2*	VLA-NUC*[a]
Aerodynamic Data							
Cruise Mach number	0.77	0.75	0.75	0.75	0.75	0.75	0.75
Initial cruise altitude (ft)	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Zero-lift drag coefficient	0.0178	0.0148	0.0151	0.0180	0.0127	0.0170	0.0133
Lift-to-drag ratio (maximum)	20.0	21.6	21.4	18.6	23.8	19.5	22.9
Propulsion Data							
Number of engines	4	6	6	6	8	6	[illegible]
Bypass ratio	8	10	10	10	3.85	10	3.85
Fan pressure ratio	1.42	1.40	1.40	1.40	1.64	1.40	1.64
Overall pressure ratio	25	35	35	35	19.5	35	19.5
Turbine inlet temperature (°F)	2,380	2,500	2,500	2,500	1,870[b]	2,500	1,870[b]
At max. sea level static power							
- Installed thrust	100	81,500	83,400	56,400	77,800	71,700	56,800
- Installed TSFC[c] (lb/hr/lb)	0.333	0.296	0.257	0.109	0.390	0.109	0.390
Cruise TSFC (lb/hr/lb)	0.675	0.624	0.542	0.230	0.680	0.230	0.680

[a]For operation on JP, unless otherwise noted.

[b]1600°F when operating in nuclear mode.

[c]Thrust specific fuel consumption.

The propulsion system data shown in Table 8 illustrates the relatively modest advances in turbofan engine state of the art assumed in the present work. For example, the maximum turbine inlet temperature for the chemical-fueled VLAs is 2500°F compared to 2380°F for the General Electric TF39 engines used on the C-5A.

Note, however, the markedly different characteristics of the dual-mode[a] turbofans for the nuclear-powered airplanes. Specifically, these engines have a much lower maximum turbine inlet temperature in the chemical mode and this is still further reduced when they operate in the nuclear mode.[b] Despite these inefficiencies, the dual-mode engines proved preferable to providing separate engines for the two propulsion modes.

Performance Characteristics

Cargo Missions. The payload capability in terms of mission range is depicted in Fig. 10a for each of the design-point very large airplanes. Corresponding results for each of the excursion-case airplanes are shown in Fig. 10b. Even though the design-point airplanes share a common payload-radius point (350,000 lb for a 3600 n mi mission), they exhibit grossly dissimilar payload-range characteristics. The nuclear airplanes are an extreme demonstration of this point since their payload capabilities are independent of mission range.

Of particular interest is the comparison of the VLA-LH_2 alternative with the VLA-JP. Note that both airplanes have comparable ranges

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[a]Called "dual-mode" because these engines can operate on either nuclear heat or chemical fuel (JP). The engines have been sized to provide the required takeoff thrust when operating on JP. In the nuclear cruise mode, they are limited by the relatively modest operating temperature of the nuclear system (see Appendix B).

[b]It would have been possible to develop an engine design which provided a much higher turbine inlet temperature during chemical-mode operation. Such an engine in the nuclear mode, however, would be grossly inefficient because of its inferior performance in this off-design condition. Thus, the engine described in Table 8 represents the best available trade-off.

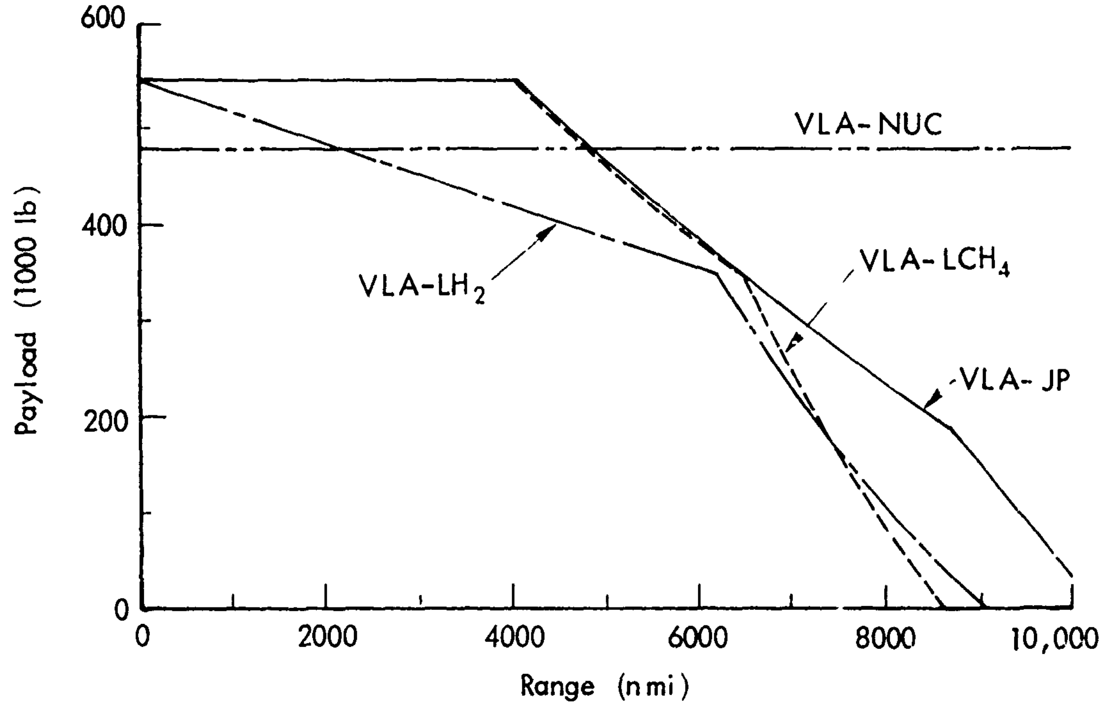

Fig. 10a — Range-payload characteristics of the design-point airplanes

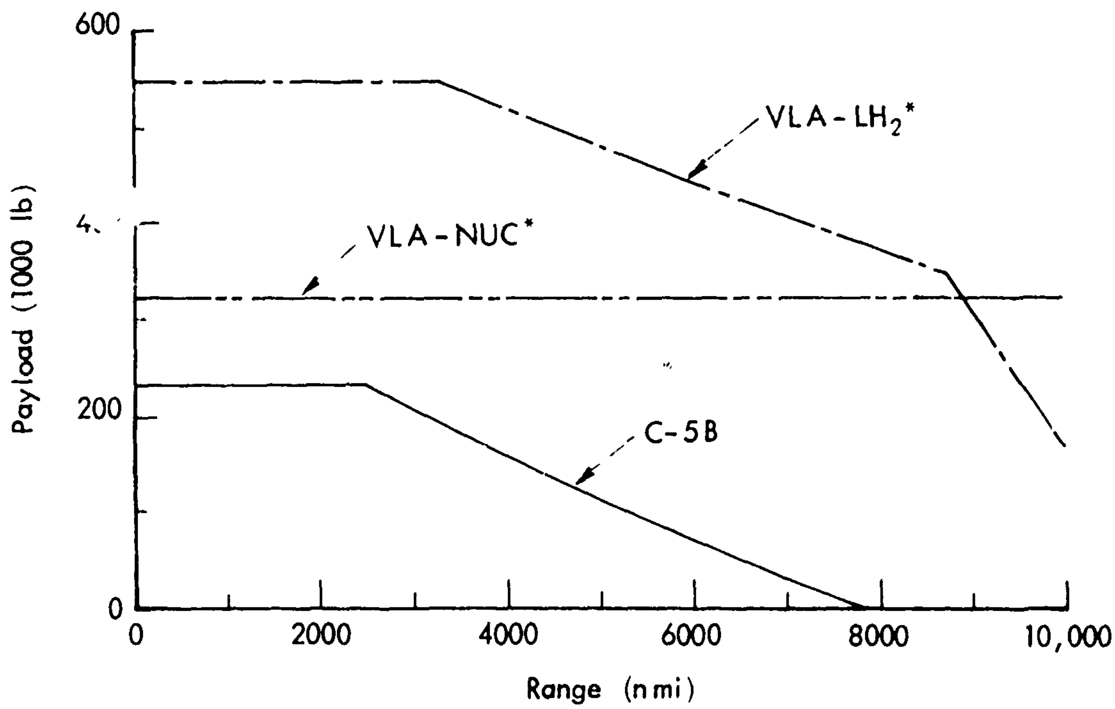

Fig. 10b — Range-payload characteristics of the excursion-case airplanes

at the design payload. However, for any other payload, the VLA-LH_2 possesses a markedly inferior range capability. For payloads above 350,000 lb, this phenomenon is a consequence of liquid hydrogen's much higher heat of combustion. That is, to increase the payload beyond 350,000 lb, fuel weight must be exchanged for additional payload weight (since the maximum gross weight remains constant). The range degradation in the case of liquid hydrogen is greater since each pound of fuel exchanged for payload results in a greater loss in available fuel-energy. For payloads less than 350,000 lb, the inferior performance of the VLA-LH_2 arises because the design payload corresponds to the Y-point. In other words, the volume available in the liquid-hydrogen fuel tanks is such that they are full at the design payload; if the payload is reduced, no tank volume is available to accept the additional fuel (and the airplane operates at a gross weight less than the maximum).

These characteristics of the VLA-LH_2 aircraft provide additional motivation for the liquid-hydrogen-fueled excursion-case aircraft. Note that the payload capability of the VLA-LH_2* is equal to or greater than that of the VLA-JP for almost all mission ranges. By including the VLA-LH_2* alternative, we have thus avoided any possible biases resulting from the above-described characteristics of liquid hydrogen as an aircraft fuel.

Figure 10 should also provide some insights into the magnitude of the increase in capability provided by the VLA. For example, at a range of 2500 n mi, the VLA-JP has more than twice the payload capacity of the C-5B. At 5500 n mi, the VLA-JP's payload is more than fourfold greater.

Tanker Missions. Figures 10a and b indicate how the alternatives might perform in the cargo role. Also of interest is their performance in the tanker role. Two classes of tanker missions must be examined: (1) the very large airplanes provide tanker support for JP-fueled airplanes (e.g., tactical fighters or strategic bombers); (2) the VLAs provide tanker support for other VLAs, which might be performing a variety of missions. In this latter case, the fuel transferred by the

VLA tanker will be the same fuel that it uses for propulsion (i.e., the VLA-LH_2 will transfer liquid hydrogen).

Figures 11a and 11b illustrate the performance of the alternative airplanes when they are transferring JP to the receiver aircraft. Once again, a wide variation in the performance of the design-point alternatives as well as of the excursion-case aircraft can be observed.[a]

We label the data on JP-tanker performance in Figs. 11a and 11b approximate since the performance of the cryogenic-fueled airplanes could be improved if the operational requirements so dictated. For example, when operating in the JP-tanker mode, the VLA-LH_2's cargo compartment is empty. If it were desired to increase JP off-load capability at mission radii greater than 3600 n mi, auxiliary cryogenic fuel tanks could be carried in the cargo compartment. Such a modification would cause the slope of the JP off-load versus radius curve to be more nearly constant. (That is, by providing additional LH_2 storage capacity, the sharp drop in JP off-load capability beyond 3600 n mi could be virtually eliminated.)

We have not analyzed the performance of the various alternatives in the JP-tanker role in detail.[b] For the present work, how the alternatives perform when providing tanker support to airplanes of the same kind is of greater interest. Figure 12a displays the fuel off-load capability of the chemical-fueled alternatives[c] as a function of mission radius. An examination of Fig. 12a suggests that the VLA-JP and VLA-LCH_4 alternatives are the best tankers.

But because fuel off-load is expressed in pounds, Fig. 12a is somewhat misleading. More important (since we are considering different

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[a]In Fig. 11 and throughout this report, C-5Bs in the tanker mode are assumed to operate at a load factor of 2.00 g (ground-maneuver limit). The corresponding maximum gross weight is 795,000 lb (see Appendix C). The rationale for this assumption will become apparent in Section IX.

[b]Additional insights into the relative attractiveness of the alternatives in the JP-tanker role can be obtained from Section VIII.

[c]The nuclear-powered airplanes, of course, do not require any inflight refueling.

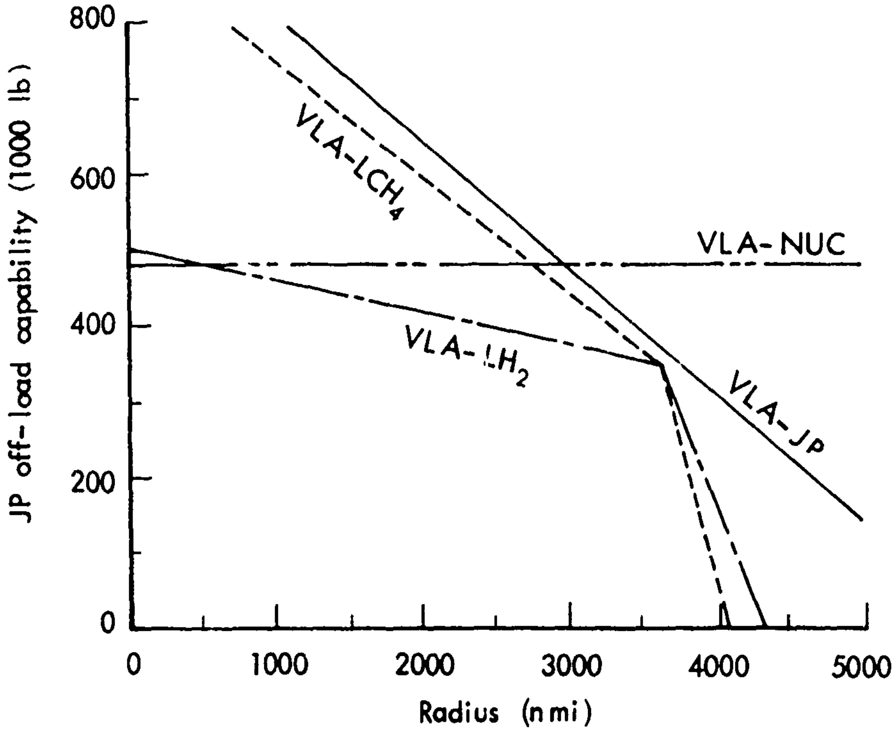

Fig. 11a — Approximate JP-tanker performance of the design point airplanes

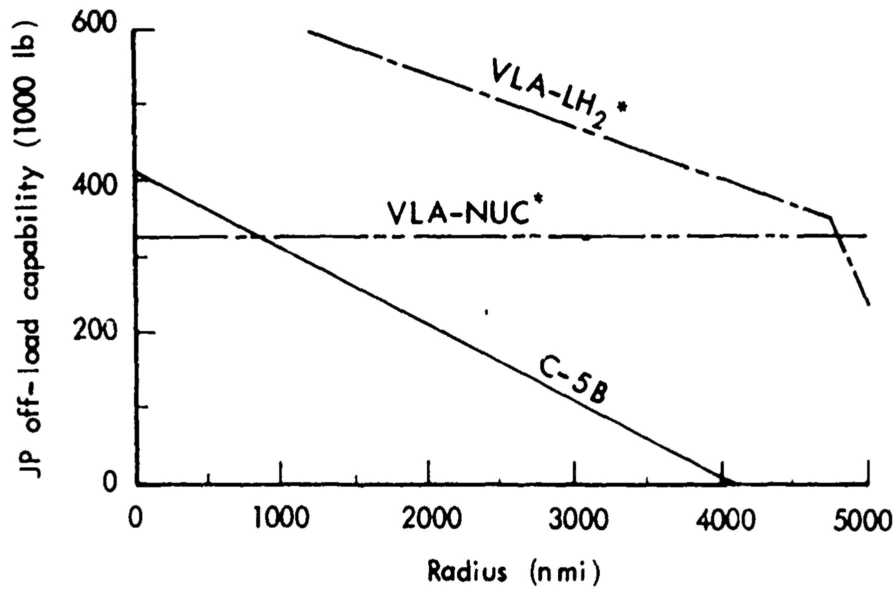

Fig. 11b -- Approximate JP-tanker performance of the excursion-case airplanes

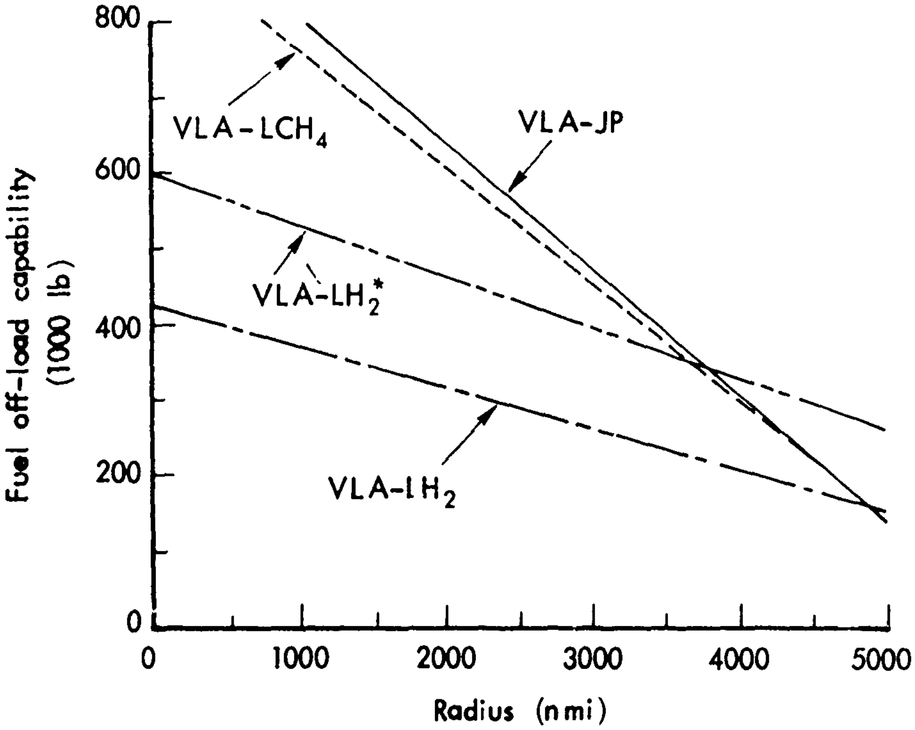

Fig. 12a — Tanker performance of chemical-fueled very large airplanes

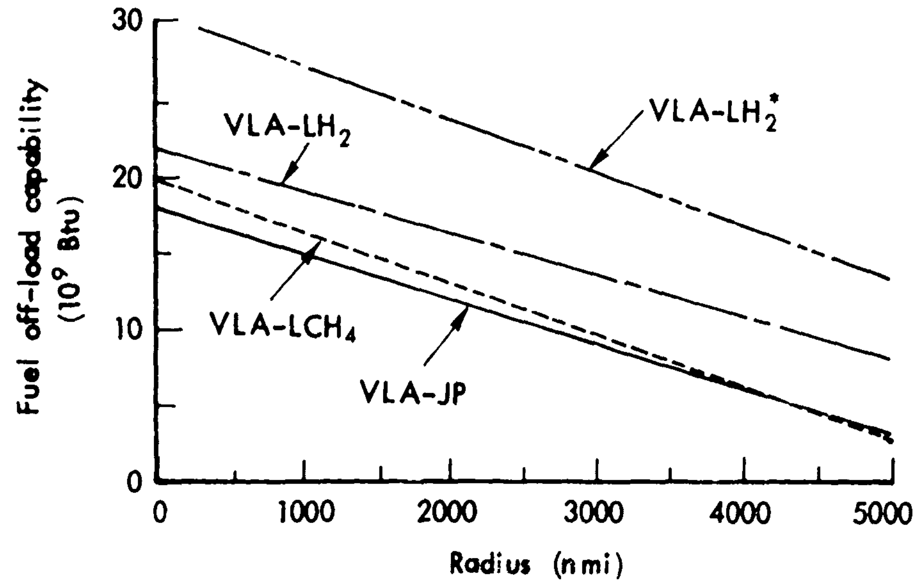

Fig. 12b — Tanker performance of chemical-fueled very large airplanes

fuels) is the energy contained in the fuel off-loaded; data on this are presented in Fig. 12b. As Fig. 12b demonstrates, the cryogenic airplanes provide the greatest fuel-energy off-load at any given radius. This occurs even though both LH_2 airplanes are fuel-volume limited rather than weight limited. That is, the additional cryogenic tanks contained in the cargo compartment provide insufficient volume to allow either of the liquid hydrogen airplanes to operate at its maximum gross weight in the cryogenic-tanker mode. (Details are included in Appendix C.)

A better perspective on the capabilities of the alternatives can be gained by examining the performance of the receiver/tanker pair with in-flight refueling (IFR) under different mission rules. Appendix C contains payload-performance figures for each alternative airplane for each of the following mission rules.

- Range (no IFR)
- Range--one IFR[a]
- Radius (no IFR)
- Radius--one IFR[a]
- Radius--two IFR[a]

Also included in Appendix C is a description of the theoretical approach used to estimate performance with in-flight refueling.

Table 9 summarizes the range/radius capabilities of each alternative with its design payload. The performance characteristics of the VLA-JP and VLA-LCH_4 with in-flight refueling are almost identical. As one would suspect from our previous discussion of energy off-load capability, both liquid hydrogen airplanes demonstrate superior range and

[a]Unless otherwise noted, a single IFR refers to an outbound refueling (buddy mission rules) with both tanker and receiver originating at the same base; the tanker returns to the originating base (i.e., the tanker flies a radius mission). Two IFRs imply an outbound refueling as described above plus an inbound refueling (rendezvous mission rules). For the second IFR, the tanker flight originates and terminates at the receiver's destination base.

Table 9

PERFORMANCE CHARACTERISTICS OF THE ALTERNATIVE AIRPLANES WITH DESIGN PAYLOADS

Performance Characteristic	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Design Payload (1000 lb)	216	350	350	350	350	425	230
Capabilities (n mi)							
Radius	1,550	3,600	3,600	3,600	(a)	3,600	(a)
Radius--one IFR[b]	3,220	5,680	5,720	6,530	-	7,100	-
Radius--two IFR[c]	4,220	7,450	7,500	8,750	-	9,650	-
Range	2,730	6,400	6,500	6,200	(d)	6,570	(e)
Range--one IFR[b]	5,340	10,500	10,350	11,340	-	12,400	-
Critical Field Lengths (ft)							
Takeoff (maximum gross weight)	8,000	8,000	8,000	8,000	8,000	8,000	8,000
Landing (radius mission)	4,500	4,750	4,900	5,500	5,940	5,500	5,940

[a]Essentially unlimited radius capability with design payload.

[b]Outbound IFR under buddy mission rules.

[c]Outbound refuel plus inbound IFR under rendezvous mission rules.

[d]Essentially unlimited range with 480,000-lb payload.

[e]Essentially unlimited range with 325,000-lb payload.

radius capabilities with aerial refueling. Again note that the payload capability of both nuclear airplanes is dependent on whether range or radius missions are being flown.

Also shown in Table 9 are the field-length requirements for each alternative. The takeoff/landing performance listed in Table 9 complies with the design goals listed in Section II. (Further details on takeoff and landing performance at other gross weights are presented in Appendix A.

Endurance Missions. The final performance feature discussed in this section is airborne endurance. Both nuclear-powered alternatives have essentially unlimited endurance when carrying payloads that correspond to a range mission (see Figs. 10a and 10b). Indeed, their characteristics are such that they can cruise any required distance to a station-keeping point, remain on-station for as long as desired (within the limits of the crew's endurance), and then return to the originating base. For this profile, the VLA-NUC's payload can be as much as 480,000 lb; the VLA-NUC*'s limit is 325,000 lb.

Endurance characteristics, in terms of the distance to the station-keeping point, are illustrated in Fig. 13 for the chemical-fueled alternatives. Interestingly, the design-point very large airplanes exhibit essentially the same trade-offs between endurance and station radius. The endurance of the VLA-LH_2* is greater than the other alternatives; the C-5B, even with the reduced payload, has poorer endurance characteristics. (The endurance capability of the VLA alternatives with other mission-payloads is contained in Appendix A.)

Of course, by relying on aerial refueling, the chemical-fueled alternatives can fly these kinds of missions at greater station-radii than indicated in Fig. 13. However, we will defer discussion of these types of mission profiles until Section VIII.

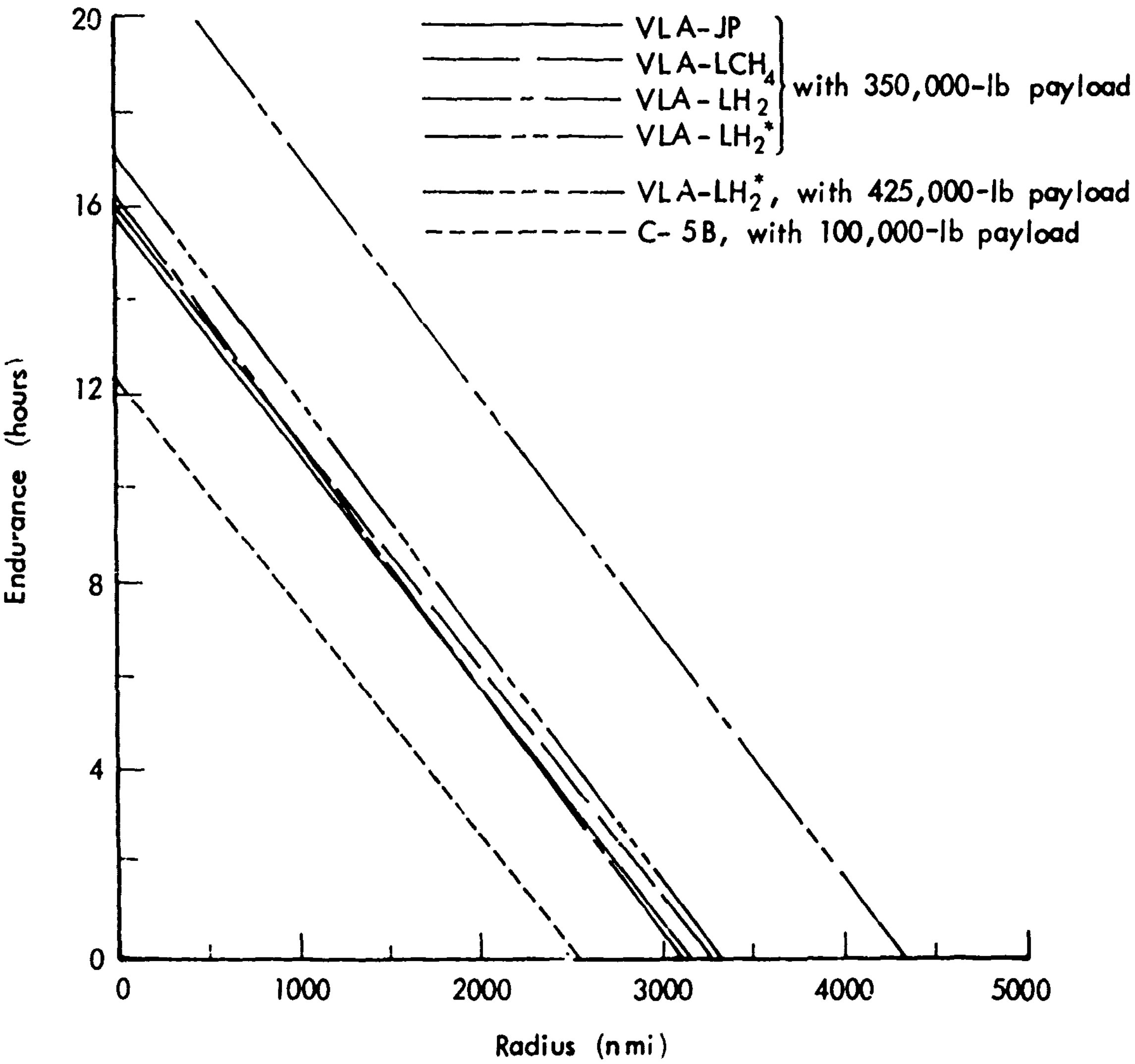

Fig. 13 — Endurance characteristics of the chemical-fueled alternatives

V. LIFE-CYCLE COST ESTIMATES

The life-cycle cost of a weapon system is the sum of its acquisition costs and its operating and support (O&S) costs over its expected life. For the class of airplane examined in this study, we believe that 20 years is an appropriate expected useful life.

Acquisition costs consist of procurement costs and research, development, test, and evaluation (RDT&E) costs. The former are termed recurring costs (i.e., dependent on the quantity of aircraft procured), the latter nonrecurring. The procurement costs are made up of the aircraft flyaway cost (which includes the airframe, engines, and avionics) plus ground support equipment, initial spares, and so on. Most elements of the procurement cost have an associated RDT&E cost.

In addition to flight-crew and fuel costs, operating and support costs include the following items:

- Squadron personnel
- Base operating support personnel
- Medical personnel
- Common AGE (aerospace ground equipment)
- Replenishment spares
- Depot maintenance
- System support
- General support

These costs depend on the number of aircraft acquired as well as the peacetime utilization (UTE) rate. Of course, the O&S costs must also reflect the desired wartime (or surge) utilization rate.

In this section, we present the life-cycle costs of the alternatives in terms of the cost elements we have been discussing. Some illustrative cost sensitivities are also discussed. (Appendix D describes the methodologies employed in the cost analysis.)

ILLUSTRATIVE LIFE-CYCLE COSTS FOR EACH ALTERNATIVE

The life-cycle cost estimates presented below are based on the procurement of 112 unit equipment (UE) aircraft (seven squadrons of 16 UE each).[a] Allowance for attrition and aircraft in the depot-maintenance pipeline make necessary a total procurement of 129 aircraft (excluding any development aircraft).

An operational consideration of clear importance to life-cycle costs is the peacetime utilization rate. Throughout this section, we have assumed 60 flying hours per month (720 hours per year) which is commensurate with current Air Force practice with the C-5A and appears appropriate for our present purposes.

Design-Point Airplanes

Table 10 displays the life-cycle cost estimates for each of the design-point very large airplanes. Recall that each of these airplanes has the capability to carry a 350,000-lb payload on a 3600 n mi radius mission. Thus, an equal number of UE aircraft also provide an equal capability--at least, for this design-mission profile. Consequently, the life-cycle costs shown in Table 10 can be interpreted as the costs of each alternative for approximately equal effectiveness.

Table 10 indicates that the acquisition costs of the VLA-NUC are substantially larger than those of the chemical-fueled alternatives. The VLA-NUC's heavier airframe as well as the additional expense of the nuclear system cause this disparity. Differences in the unit fly-away costs of the chemical-fueled airplanes are also significant, with the VLA-LH_2 the least expensive due to its more modest gross weight and empty weight characteristics. The RDT&E costs of the VLA-JP, VLA-LCH_4, and VLA-LH_2 are comparable.

Substantial differences in the 20-year O&S costs of the four alternatives can be observed. Crew costs are greater for the VLA-NUC since additional personnel are required for the nuclear

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[a]The reason for selecting 112 UE aircraft for this example will become apparent in Section VII.

Table 10

ESTIMATES OF LIFE-CYCLE COSTS FOR THE DESIGN-POINT ALTERNATIVES
(Billions of 1975 dollars, unless otherwise stated)

Cost Element	Alternative			
	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC
Procurement Total	(11.88)	(12.67)	(10.35)	(24.89)
Airframe	8.19	8.86	7.24	12.62
Engines	1.86	1.88	1.50	1.36
Nuclear system	-	-	-	6.95
Other[a]	1.83	1.93	1.60	3.96
RDT&E Total	(3.60)	(3.85)	(3.21)	(7.16)
Airframe	2.98	3.20	2.65	4.45
Engines	0.29	0.29	0.27	0.19
Nuclear system	-	-	-	1.69
Other	0.33	0.36	0.30	0.83
20-Year O&S Total	(16.44)	(18.83)	(21.34)	(24.58)
Crew	1.10	1.10	1.10	1.47
Fuel	3.68	5.24	9.90	3.49[b]
Maintenance, fixed facilities, etc.	11.66	12.49	10.35	19.62
20-Year Life-Cycle Total	31.92	35.35	34.92	56.63
Number of Aircraft Procured	129	129	129	129
Unit Flyaway Cost (millions of 1975 dollars)	79.2	84.5	69.0	163.5

NOTE: Based on the procurement of 112 UE aircraft and an average UTE rate of 720 flying hours per year.

[a] Includes avionics, ground support equipment, initial spares, etc.

[b] Includes nuclear fuel and JP costs.

system.[a] Of greater importance, however, are the VLA-NUC's much larger costs for maintenance, fixed facilities, etc. Again, these are a consequence of the additional support costs of the nuclear system and the greater size of the nuclear airplane.

Synthesis of the Chemical Fuels

Before discussing the costs of the alternative fuels, consideration must be given to how the chemical fuels might be synthesized. A basic ground rule, stated earlier, is that each of the alternatives must be obtainable from a primary energy resource other than petroleum or natural gas. That this has been observed for the three fuels of interest is illustrated in Fig. 14. Available primary energy resources are noted at the top of Fig. 14, which also shows the various paths leading to the synthetic fuel end-products. Although Fig. 14 does not include all possible process paths, it is representative of the processes most frequently discussed in the literature. We have included methanol as one of the end-products because of its potential as a ground-transportation fuel [44]. Were methanol to be widely available for this purpose, it could be envisioned as an intermediate energy carrier for subsequent use in the synthesis of either liquid methane or liquid hydrogen.

A careful examination of Fig. 14 reveals that several of the primary energy resources can be used to manufacture any of the end-use synthetic fuels. Most notable, in this category, is coal. Data from

[a]Here and throughout the report, unless noted otherwise, sufficient air crews, maintenance personnel, etc., are provided to allow for a wartime operational readiness (OR) rate of 0.58. (Under surge conditions, we assume an aircraft that is operationally ready will be either flying, taxiing, or being loaded, unloaded, or refueled [43].) An OR rate of 0.58 yields wartime utilization rates between about 10 and 13 hours per day--depending on the aircraft and scenario being considered. Specifically, an OR rate of 0.58 for the C-141A corresponds to an average utilization rate of 10 flying hours per day during a NATO reinforcement, assuming all aircraft fly range-mission profiles. (See Section VII for additional discussion of the implications of using a constant OR rate.)

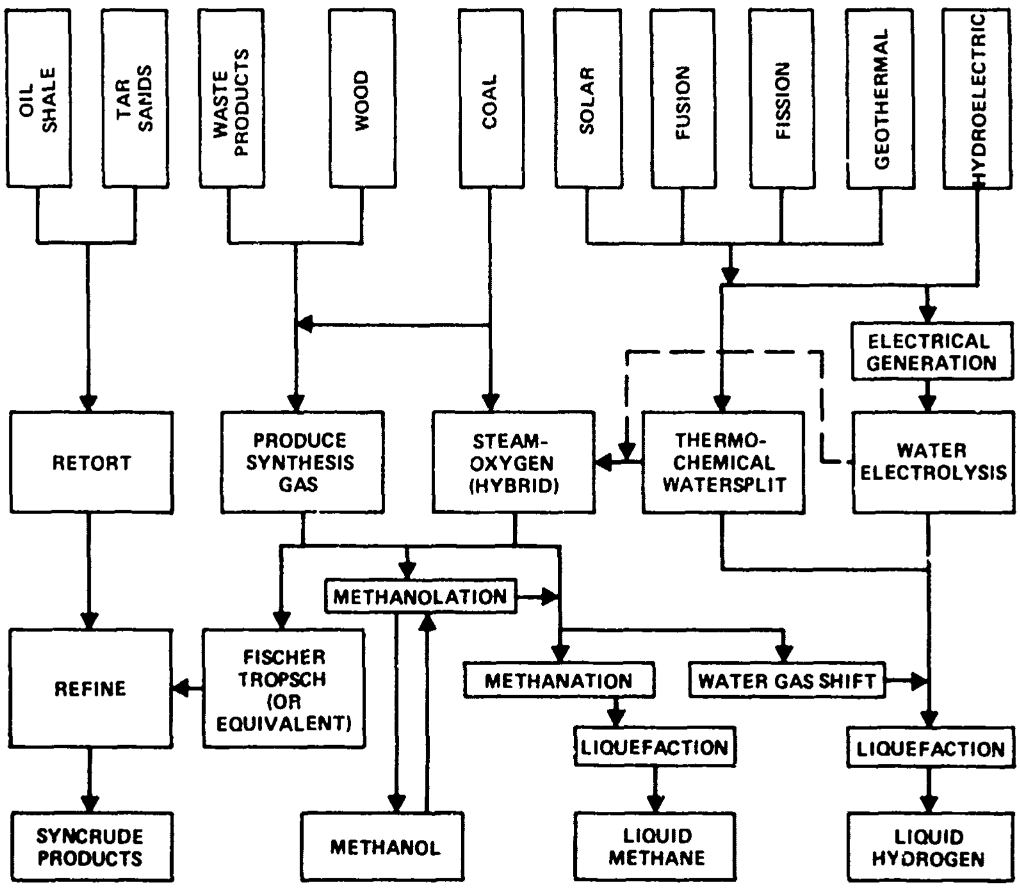

Fig. 14 — Representative synthetic-fuel supply processes

ERDA demonstrates that coal is the most abundant of the nonrenewable U.S. energy resources (at least, until the breeder reactor program proves commercially successful) [14]. Furthermore, (1) the extraction of coal, either by strip or deep mining, is obviously a mature and well-developed technology; (2) developing economic technologies for converting coal to gaseous and liquid fuels is a major element of current U.S. energy research; and (3) these R&D programs are scheduled to provide the needed technologies in the time frame of interest to the present work. For these reasons, we have selected

coal as the universal starting point in the supply process for each of the synthetic chemical fuels under consideration. (Details of the analysis of the cost and energy implications of these processes are described elsewhere [19].)

Also of interest in Fig. 14 is the observation that liquid hydrogen is the only alternative fuel that can readily be derived from the so-called renewable energy resources.[a] Of principal interest among such resources are solar energy and fusion, which, as noted in Section I, can be expected to assume ever-increasing importance in future years. In view of this, one can expect that liquid hydrogen will eventually be employed as a fuel for aircraft as well as for other modes of transportation.

For our present purposes, however, we must be concerned with the relative attractiveness of synthesizing LH_2 from coal or using a nonorganic resource to produce it. Nuclear fission offers the greatest potential as a nonorganic resource (see Section I). The state-of-the-art procedure would be first to generate electricity in a light water reactor and then obtain hydrogen by the electrolysis of water. All available studies have indicated that this approach is substantially more costly and more energy intensive than a coal gasification process [36,41,45].

Advanced technology concepts include using fission reactors to supply process heat to either closed-cycle or open-cycle thermochemical water-splitting processes. Although the former concept has yet to be demonstrated successfully in the laboratory [46], some recent successes have been reported with the latter [47]. For this, costs at least comparable to hydrogen synthesis from coal seem possible.

In view of the economics of manufacturing hydrogen from nonorganic sources, the choice of coal as the universal primary energy resource seems appropriate--particularly for the time frame of interest in the present study.

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[a]We are discounting the possibility of using a carbon source such as limestone (or carbon extracted from carbon dioxide in the atmosphere) in conjunction with renewable energy resources to synthesize the carbonaceous fuels.

Fuel Costs

Table 10 indicates that fuel costs account for many of the differences in the life-cycle costs of chemical-fueled airplanes. W. L. Stanley, of Rand, has developed estimates for the unit cost of the chemical fuels assuming their synthesis from coal [19,48]. In 1975 dollars, he estimates the unit fuel costs to be about \$3.20/MMBtu (million Btu) for synthetic JP,[a] \$4.30/MMBtu for liquid methane, and \$9.80/MMBtu for liquid hydrogen. A breakdown of these net costs is presented in Fig. 15. (The large by-product credit for synthetic JP is largely accounted for by the substantial quantity of high-octane unleaded gasoline produced in the syncrude refining step.) The cost estimates shown in Fig. 15 are near the middle of the range of estimates developed by Stanley [19].

The average unit price of enriched uranium for the nuclear airplane was estimated at \$0.65/MMBtu (see Appendix E). Despite this much lower unit energy cost, the 20-year fuel cost shown in Table 10 for the VLA-NUC is comparable to that of the VLA-JP. This somewhat surprising result obtains for two reasons: (1) The VLA-NUC is relatively more energy intensive than the VLA-JP because of its much greater average in-flight gross weight and its relatively inefficient engines.[b] (2) The VLA-NUC requires a great deal of JP for takeoffs and landings (see Appendix A); the unit cost of this JP is assumed to be 39 cents per gallon.

A comparison of total life-cycle costs in Table 10 indicates that the VLA-LH_2 loses its advantage in acquisition costs over the VLA-JP because of the much higher cost of LH_2. Moreover, the life-cycle costs

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[a]For synthetic JP, this corresponds to about 39 cents per gallon. Of course, the life-cycle cost estimates for the VLA-JP are also valid if the JP is derived from crude oil and priced at 39 cents per gallon. In the third quarter of 1975, the Air Force paid the Defense Fuel Supply Center an average of 42 cents per gallon for JP-4 [48]. In this analysis, the synthetic JP is more similar to JP-8 than to JP-4--as JP-8 is more easily obtained from coal-derived liquids [19].

[b]The energy intensiveness of the VLA-NUC is further discussed in the section on life-cycle energy consumption (Section VI).

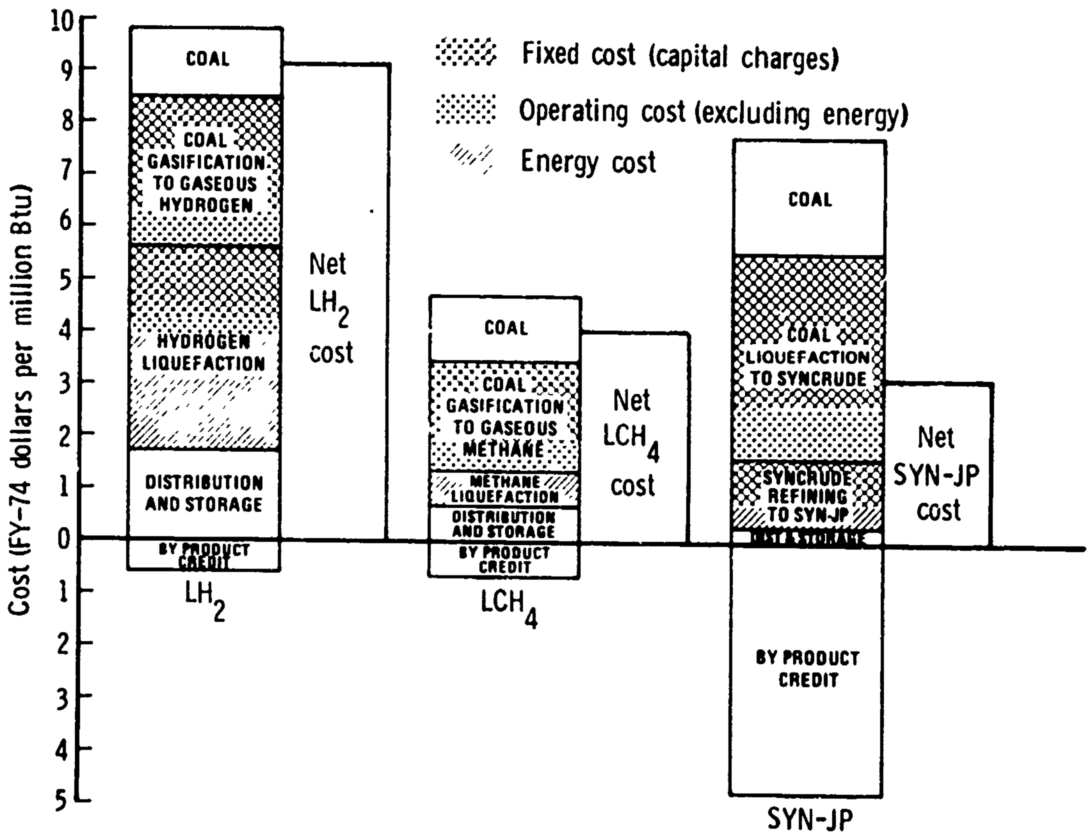

Fig.15—Cost estimates for the synthetic fuels [19]

of the VLA-NUC are almost twice that of the VLA-JP. (Whether or not the VLA-NUC's essentially unlimited range/radius/endurance capabilities are enough to overcome its cost disadvantages is one of the principal questions addressed in the remainder of this report.)

The sensitivity of the unit fuel costs used in our analysis to variations in the input price of coal, etc. is discussed elsewhere [19,48].[a] However, Table 10 demonstrates that fuel represents a small --but nonetheless not trivial--component of total life-cycle costs. For example, a 50 percent increase in the average unit cost of JP would increase the life-cycle costs by about 1.8 billion dollars or less than 6 percent of the total. A similar 50 percent increase for the VLA-NUC

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[a]We will also discuss some of these sensitivities further in Section IX.

would increase its fuel costs by about the same absolute amount, but would represent a much smaller percentage of total costs. Obviously, a 50 percent change in the unit cost of liquid hydrogen would have a much greater impact.[a]

Excursion-Case Airplanes

Similar life-cycle cost estimates for the three excursion-case airplanes are presented in Table 11. These estimates are also based on the procurement of 112 UE aircraft, but because an equal number of UE does not correspond to equal effectiveness, these costs cannot be compared directly with those of the design-point alternatives. (In Section VII, we will develop a constant-capability case in which costs can be directly compared; furthermore, measures of cost-effectiveness will also be developed.)

C-5B costs were estimated with the same methodology used for the other alternatives. The fact that similar aircraft (C-5As) have already been procured but the production line has closed down makes our costing fraught with uncertainty. For example, the RDT&E costs shown in Table 11 presume that two C-5B development aircraft would be required. (Five VLA development aircraft are assumed.) If the presently planned wing modifications to the existing C-5A fleet proceed [49], perhaps one (or both) of the development aircraft could be eliminated. Under such circumstances, total development costs could be reduced to as little as 200 million dollars. But despite the uncertainty, the C-5B life-cycle cost estimates should be adequate for the purposes of the present study.

SOME SENSITIVITIES FOR THE VLA-JP

Numerous factors affect the estimation of aircraft life-cycle costs. Some are related to the acquisition strategy; others involve

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[a]We should also note that these unit fuel costs are based on the actual cost of producing the synthetic fuel, including a reasonable return on investment [19]. They are not intended, however, to reflect fuel prices under actual market conditions. For example, the actual cost of extracting crude oil in the Middle East is only a small fraction of the market price of crude oil set by OPEC. To predict such "market prices" for any of the synthetic fuels or for nuclear fuel is beyond the scope of the present analysis.

Table 11

ESTIMATES OF LIFE-CYCLE COSTS FOR THE EXCURSION-CASE ALTERNATIVES
(Billions of 1975 dollars, unless otherwise noted)

Cost Element	Alternative		
	C-5B	VLA-LH_2*	VLA-NUC*
Procurement Total	(4.50)	(12.43)	(19.07)
Airframe	3.19	6.82	9.03
Engines	0.50	1.72	1.11
Nuclear system	-	-	5.81
Other	0.81	1.89	3.12
RDT&E Total	(1.16)	(3.80)	(5.81)
Airframe	1.06	3.17	3.26
Engines	-	0.28	0.16
Nuclear system	-	-	1.69
Other	0.10	0.35	0.70
20-Year O&S Total	(9.24)	(26.01)	(18.63)
Crew	1.10	1.10	1.47[a]
Fuel	2.41	12.38	2.55
Maintenance, fixed facilities, etc.	5.73	12.53	14.61
20-Year Life-Cycle Total	14.90	42.24	43.51
Number of Aircraft Procured	129	129	129
Unit Flyaway Cost (millions of 1975 dollars)	29.2	82.9	125.0

NOTE: Based on the procurement of 112 UE aircraft and an average UTE rate of 720 flying hours per year.

[a]Includes nuclear fuel and JP costs.

analytical uncertainty in the costing methodologies. Below we provide two specific examples. The first shows the sensitivity to the number of aircraft procured and the second illustrates the potential errors in the estimates for the VLA-class aircraft.

Effect of Production Quantity

Table 12 presents VLA-JP life-cycle costs for various procurement quantities. Note that development costs are identical for all three quantities but that there is a very substantial variation in unit flyaway costs. Procuring 224 UE rather than only 48 reduces the average unit flyaway cost *by more than 50 percent*. Similar effects can be observed with the total life-cycle costs. For 48 UE, the average life-cycle cost per UE is 380 million dollars; if 224 UE are procured, this figure is reduced to only 139 million dollars per UE. Obviously, how expensive a particular aircraft is perceived to be is very dependent on how many airplanes are eventually procured.[a]

Effect of Potential Errors

We mentioned in Section IV that estimating the costs (and other aspects) of large airplanes is particularly difficult because they are far removed from the data base of existing aircraft. Table 13, which displays three cost estimates for the VLA-JP, provides insights into the significance of this analytic difficulty. The low and high estimates are based on cost estimating relationships developed by Rand (described in Appendix D[b]). The nominal estimate is based on

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[a]Interestingly, all of the VLA alternatives exhibit similar cost characteristics as the number of UE procured increases except the nuclear airplanes. This is a consequence of our using a much more modest learning curve for the nuclear reactor system. (Indeed, for the nuclear reactor itself, the estimates postulate no effect from the learning curve [10].) Of course, we may be overly pessimistic since such a reactor has yet to be built. However, experience to date indicates that the effect of the learning curve is considerably less dramatic for nuclear reactors (see Appendix D).

[b]Appendix D also contains further data on the costs of each alternative. Included are acquisition costs (low, high, and nominal estimates) in terms of the number of UE procured and 20-year O&S cost estimates for different assumptions regarding the peacetime utilization rate (2, 4, and 10 flying hours per day).

Table 12

THE EFFECT OF PROCUREMENT QUANTITY ON VLA-JP LIFE-CYCLE COST ESTIMATES
(Billions of 1975 dollars, unless otherwise noted)

Cost Element	UE Aircraft Procured		
	48	112	224
Procurement Total	(7.05)	(11.88)	(18.27)
Airframe	4.81	8.19	12.43
Engines[a]	1.18	1.86	2.91
Other	1.06	1.83	2.92
RDT&E Total	(3.60)	(3.60)	(3.60)
Airframe	2.97	2.97	2.97
Engines	0.29	0.29	0.29
Other	0.33	0.33	0.33
20-Year O&S Total	(7.70)	(16.44)	(31.08)
Crew	0.47	1.10	2.21
Fuel	1.58	3.68	7.36
Maintenance, fixed facilities, etc.	5.65	11.66	21.53
20-Year Life-Cycle Total	18.34	31.91	52.95
Number of Aircraft Procured	55	129	258
Unit Flyaway Cost (millions of 1975 dollars)	130.3	79.2	60.7

NOTE: O&S cost for an average UTE rate of 720 flying hours per year.

[a]Includes some continuing development cost [89]; cost-quantity reduction for engine manufacture only is based on an 85 percent slope for the cost-quantity curve.

Table 13

THE RANGE OF LIFE-CYCLE COST ESTIMATES FOR THE VLA-JP[a]
(Billions of 1975 dollars, unless otherwise noted)

Cost Element	Cost Estimate		
	Low	Nominal	High
Procurement Total	(9.76)	(11.88)	(14.17)
Airframe	6.64	8.19	9.87
Engines	1.61	1.86	2.22
Other	1.51	1.83	2.08
RDT&E Total	(2.78)	(3.60)	(4.52)
Airframe	2.46	2.98	3.53
Engines	0.10	0.29	0.55
Other	0.22	0.33	0.44
20-Year O&S Total	(14.39)	(16.44)	(18.48)
Crew	1.10	1.10	1.10
Fuel	3.68	3.68	3.68
Maintenance, fixed facilities, etc.	9.61	11.66	13.70
20-Year Life-Cycle Total	26.93	31.92	37.16
Number of Aircraft Procured	129	129	129
Unit Flyaway Cost (millions of 1975 dollars)	65.2	79.2	95.0

[a]Note: Based on the procurement of 112 UE aircraft and an average UTE rate of 720 flying hours per year.

the average cost calculated with the available estimating relationships for each cost category. (All costs throughout this report correspond to this nominal estimate.)

Table 13 shows a spread of about 30 million dollars in unit flyaway-cost estimates. Similarly, the high and low life-cycle cost estimates deviate about 16 percent from the nominal.

Given this kind of uncertainty, we cannot attach a high degree of confidence to our cost estimates--at least in an absolute sense.

We believe, however, that the estimates do have a value for indicating relative costs. That is, comparisons of the life-cycle costs of the VLA-JP and the VLA-LH_2 should be more meaningful and accurate than the variation in cost estimates exhibited in Table 13 suggests.

Moreover, estimates of life-cycle costs made by ASD as part of their VLA design work prove to be in the same general range as Rand's.[a] Figure 16 compares these two sets of estimates. Observe that for all of the alternatives the difference between the ASD and Rand cost estimates is less than 10 percent.[b]

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[a]ASD's methodology is briefly explained in Appendix D.

[b]Note that Fig. 16 is based on the procurement of a total of 112 aircraft of each type--that is, without the pipeline and attrition aircraft included in our previous estimates.

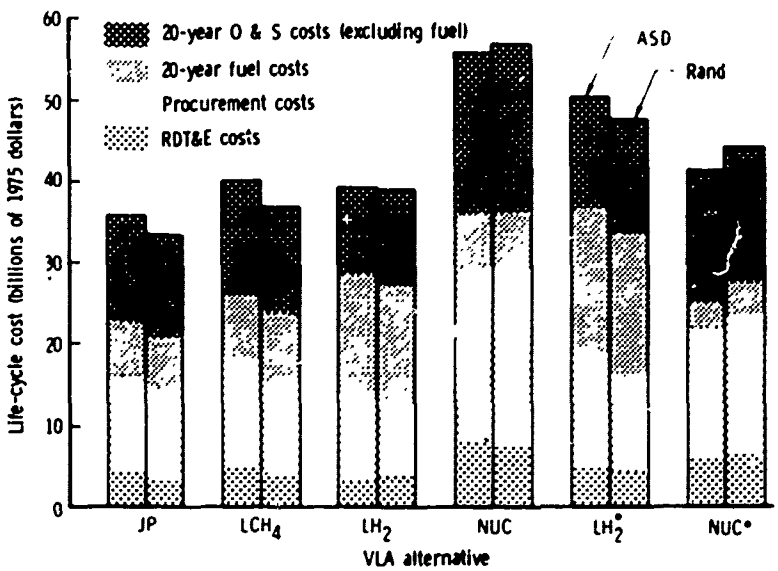

Fig. 16 — Comparison of ASD and Rand life-cycle cost estimates for 112 aircraft operating at 720 flying hours/year/aircraft

VI. LIFE-CYCLE ENERGY CONSUMPTION ESTIMATES

We have defined the life-cycle energy consumption of a fleet of aircraft as the energy expended in aircraft acquisition plus that associated with 20 years of aircraft operation. This latter quantity, termed the O&S energy, is approximated by the fuel consumed by the aircraft during their life cycle. Acquisition energy depends on the quantity of aircraft procured; O&S energy depends on the number of aircraft and is also a function of the assumed utilization rate. In this section, the life-cycle energy consumption of the four design-point alternatives is illustrated using procurement/utilization rate assumptions identical to those of the preceding section: 112 UE aircraft and 720 flying hours per year (with allowance for the depot-maintenance pipeline and attrition). The results are presented in terms of both direct and total energy consumption.

DIRECT ENERGY CONSUMPTION

As the term implies, direct energy consumption is the energy directly consumed in building and flying the aircraft. Aircraft acquisition energy, for example, includes all of the energy consumed by the aircraft manufacturing facility (e.g., electricity for lighting, for running the machines that fabricate parts, etc.). The direct O&S energy consumption is the energy content of the fuel consumed by the aircraft fleet (based on the gravimetric heats of combustion shown in Table 3).

The direct energy consumption of the four design-point airplanes is depicted in Table 14. Note that the life-cycle consumptions of the three chemical-fueled alternatives are comparable, with a slight advantage accruing to the liquid-hydrogen-fueled airplane. The VLA-LH_2 is the least energy-intensive because of the lower gross weight (and concomitant lower empty weight) provided by this high-energy-density fuel.

Observe, however, that the energy-intensiveness of the VLA-NUC is about thrice that of the chemical-fueled airplanes. As already

Table 14

ILLUSTRATIVE LIFE-CYCLE *DIRECT* ENERGY CONSUMPTION
FOR THE DESIGN-POINT ALTERNATIVES
(Quads)

Aircraft	Acquisition	20-Years' Fuel	Total
VLA-JP	0.04	1.15	1.19
VLA-LCH_4	0.04	1.22	1.26
VLA-LH_2	0.03	1.01	1.04
VLA-NUC	0.09	3.43[a]	3.52

NOTE: Based on the procurement of 112 UE aircraft and on an average UTE rate of 720 flying hours per year.

[a]Includes JP consumption of 0.51 Quads.

noted, the VLA-NUC requires more energy just to maintain steady-state flight because it has a significantly higher average in-flight gross weight. Equally important is the reduced turbine inlet temperature for the dual-mode engines necessitated by the temperature limitations of the nuclear reactor system. (Recall that these engines operate in the nuclear mode at a turbine inlet temperature of only 1600°F compared to a maximum of 2500°F for the chemical-fueled engines.) That the propulsive efficiency of a turbine engine is strongly dependent on the maximum turbine inlet temperature [50] is reflected in these results. Note that the energy consumption of the VLA-NUC also includes the JP consumed during takeoffs and landings.

Although interesting insights can be obtained by comparing the direct energy consumption of the alternatives, we believe that direct consumption is an inappropriate measure of life-cycle energy and that the alternatives ought to be judged by their life-cycle *total* energy consumption.

TOTAL ENERGY CONSUMPTION

Total energy can best be defined through the example of fuel energy. Direct energy consumption is the energy content of the fuel

consumed on board the aircraft; total energy consumption includes all of the energy expended in the fuel supply process as well.

Fuel Energy

Figure 17 displays the total energy input for each unit of useful energy output (i.e., fuel plus useful by-products) for the

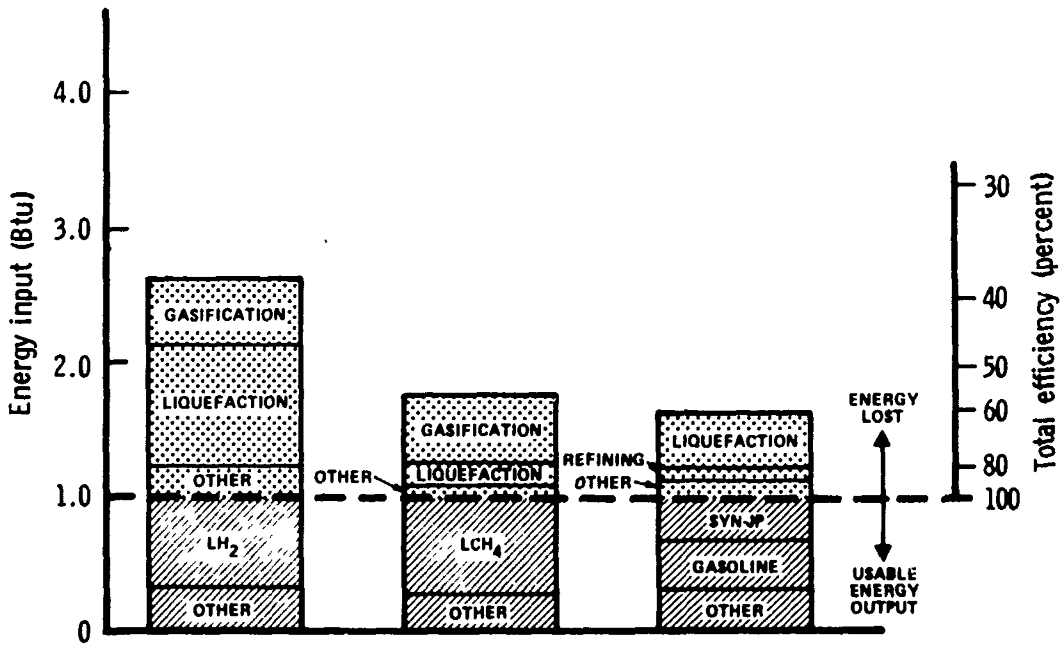

Fig. 17 — Total energy input to obtain one Btu of output energy in the form of synthetic fuel plus useful by-products [19]

three synthetic chemical fuels. (Again, we are assuming that all three are being synthesized from coal [19].) Energy expended beyond the useful output (i.e., the energy lost) includes

- Thermodynamic losses in the various conversion steps (e.g., coal gasification or liquefaction)

- Process energy requirements (e.g., electricity required to liquefy the cryogenic fuels)
- Distribution and storage losses
- Energy expended in building the required facilities

Figure 17 reveals that about 2.6 Btu's must be expended for each output Btu of liquid hydrogen and by-product. The corresponding energy ratio for liquid methane is approximately 1.8 and about 1.6 for synthetic JP.[a] Thus, the total fuel-energy consumption can be obtained through multiplying the direct consumption by the appropriate energy ratio.

Development of an analogous energy ratio for the fuel cycle of the nuclear airplane is illustrated in Fig. 18. The depicted resource energy flows are based on the energy content of the fissionable uranium isotope.[b] Note that the principal process energy input is that required for enrichment. Also, we have assumed that most of the unused energy embodied in the reactor core at the end of 10,000 reactor-hours is recoverable. With this rather conservative[c] view of the nuclear-fuel cycle, the total-energy ratio is approximately 1.5. (The details of the fuel-cycle analysis for aircraft nuclear reactors are discussed in Appendix E.)

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[a] These values are based on the incorporation of advanced-technology in the supply processes. With existing technology, the energy ratios for LH_2, LCH_4, and synthetic JP would be 3.2, 1.9, and 1.7, respectively [19].

[b] The fissionable isotope of uranium "burned" in the aircraft reactor is U^{235}. Only about 0.7 percent of uranium oxide (U_3O_8) ore is U^{235}--the rest being U^{238} which is not fissionable. Ground-based light water reactors require the fuel to be enriched to about 3 percent U^{235}. The average enrichment of the airborne liquid metal reactor's fuel is approximately 60 percent. (See Appendix E.)

[c] Conservative in the sense that, depending on the viewpoint taken, the energy ratio for the nuclear-fuel cycle could be significantly larger.

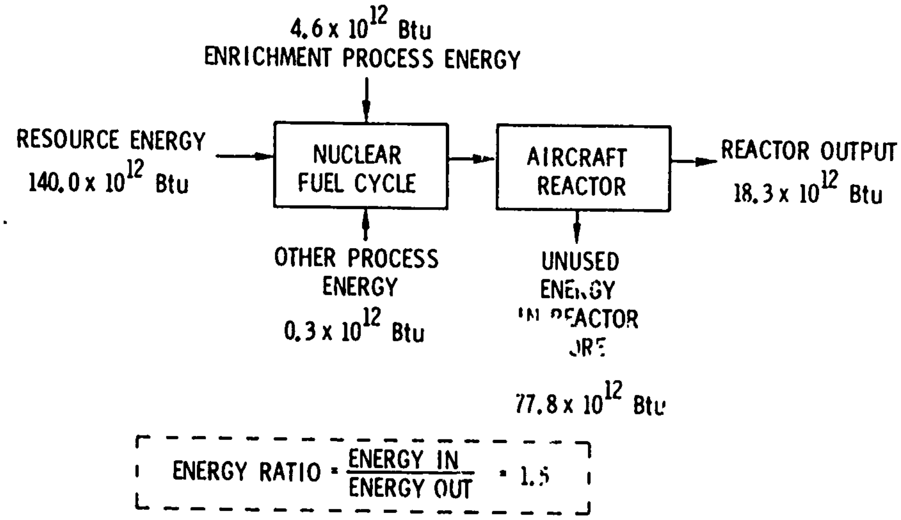

Fig. 18 — Energy flows (based on 10,000 reactor-hours for the VLA-NUC) in the fuel cycle for an aircraft nuclear reactor (from Appendix E)

Acquisition Energy

To complete the determination of total energy consumption, we must also include the total energy of aircraft acquisition. This includes, for example, energy consumed in manufacturing the aluminum from which aircraft parts are fabricated.

Our technique for estimating the total acquisition energy is based on approximate relationships between energy consumed and dollars expended in various industrial sectors. Table 15 displays such factors for both direct and total energy consumption. These factors are based on an input/output analysis of the U.S. economy which emphasized those industries supporting national defense [51].[a] As such,

[a]Total consumption factors are estimated by apportioning the total energy consumption of the United States to the various industrial sectors in accordance with their requirements for energy, material, etc.

Table 15

ENERGY INTENSITY OF AIRCRAFT ACQUISITION [50]
(In million Btu per 1975 dollars expended)

Category	Direct Energy	Total Energy
Airframe	0.0018	0.0145
Engines	0.0055	0.0334
Avionics	0.0028	0.0208
Initial Spares, etc.	0.0035	0.0263

the results for total acquisition-energy consumption should be regarded as first-order approximations. Since the acquisition energy is small compared to fuel energy, the approach is sufficiently accurate for present purposes.

Life-Cycle Energy Consumption

Table 16 summarizes the life-cycle total energy consumption for each of the design-point very large airplanes. Because of the

Table 16

ILLUSTRATIVE LIFE-CYCLE *TOTAL* ENERGY CONSUMPTION
FOR THE DESIGN-POINT ALTERNATIVES
(Quads)

Aircraft	Acquisition	20-Years' Fuel	Total
VLA-JP	0.29	1.84	2.13
VLA-LCH_4	0.31	2.20	2.51
VLA-LH_2	0.25	2.63	2.88
VLA-NUC	0.65	5.25[a]	5.90

NOTE: Based on the procurement of 112 UE aircraft and on an average UTE rate of 720 flying hours per year.

[a]Include JP consumption of 0.81 Quads.

energy-intensiveness of the liquid-hydrogen supply process, the VLA-LH_2 is the largest consumer of total energy among the chemical-fueled alternatives. Interestingly, if the JP were refined from crude oil, the VLA-JP would appear even more favorable since the fuel's energy ratio under these circumstances would be about 1.2 [48].

The VLA-NUC remains the most energy-intensive of all the design-point alternatives. However, comparing the VLA-NUC with the chemical-fueled airplanes is difficult because of the different resource bases being exploited. For example, if nuclear energy were far more abundant than coal, then the greater energy-intensiveness of the nuclear airplane might be of little significance. However, when comparing the energy consumption of alternatives which exploit different energy resources, the magnitude of the pertinent resource bases must be taken into consideration.

ENERGY RESOURCE DEPLETION

Figure 19 displays the most recently available estimates of recoverable primary energy resources within the U.S. The relative abundance of each resource is depicted by its area in the figure. Unshaded areas represent the portion of the resource economically recoverable with present technology. Also shown, for reference purposes, is the anticipated range of cumulative U.S. energy requirements through the end of the century.

We here assume (as we have throughout this report) that each of the alternative chemical fuels is synthesized from coal. As noted previously, the reliance on coal is appropriate since it is the most abundant of all the nonnuclear and nonsolar energy resources. Indeed, Fig. 19 indicates that the presently recoverable coal resource base exceeds the sum of these other resources--even with advanced technology.

How should the alternatives be judged in terms of energy resource depletion? As a first step, their life-cycle *total* energy consumption can be compared to the size of the appropriate resource base, shown in Fig. 19. For this purpose, Table 17 presents the estimates of life-cycle total energy consumption for each alternative. These estimates

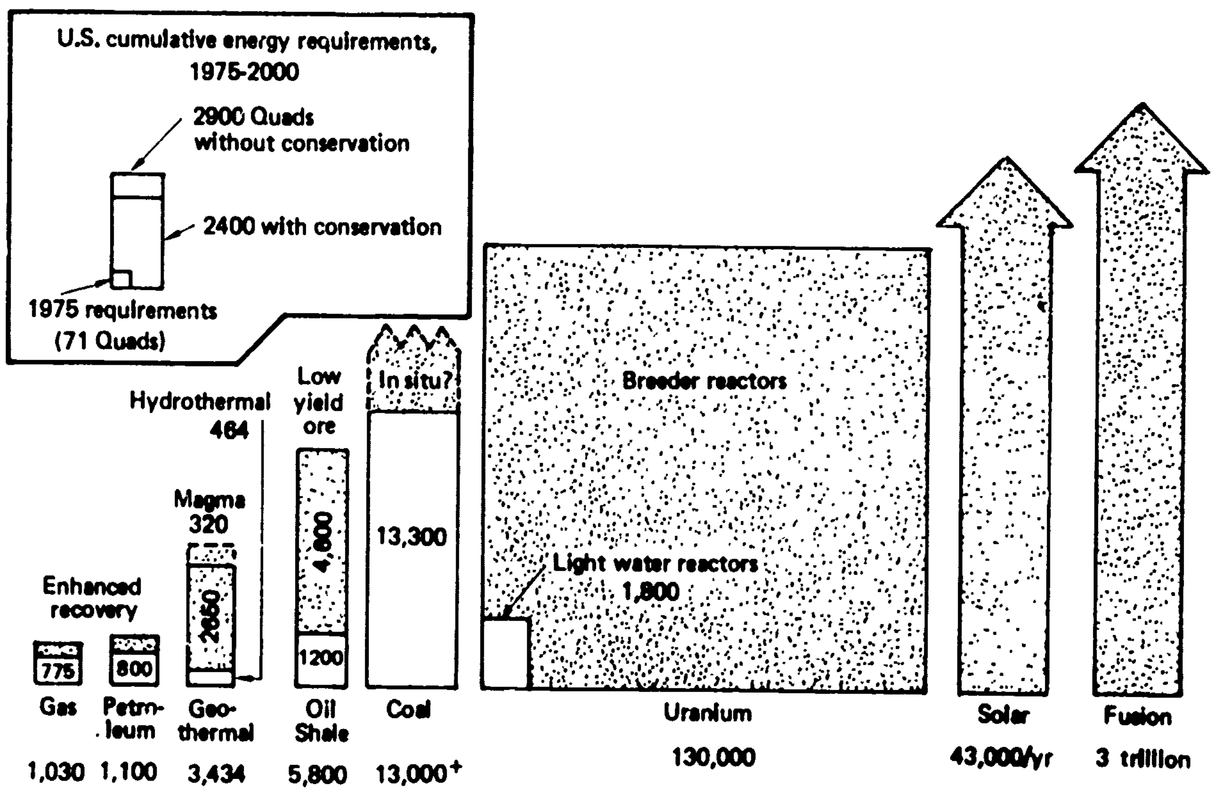

Fig. 19 — Potentially recoverable domestic energy resources in Quads [52]

Table 17

TOTAL ENERGY CONSUMPTION OF THE ALTERNATIVES
(Quads)

Alternative	Airlift Fleet[a]	Station-keeping Fleet[b]	Both Fleets
C-5B	2.58	15.37	17.95
VLA-JP	2.13	12.35	14.48
VLA-LCH_4	2.51	14.95	17.46
VLA-LH_2	2.88	17.91	20.79
VLA-NUC	5.90	33.36	39.26
VLA-LH_2*	3.10	18.92	22.02
VLA-NUC*	7.37	42.04	49.41

[a]Extracted from Table 20.

[b]Extracted from Table 23.

assume that the aircraft serve in both the airlift role (discussed in Section VII) and in a station-keeping role (Section VIII).

Chemical-Fueled Alternatives

Comparisons between the chemical-fueled alternatives is straightforward since all are depleting the same resource. Their life-cycle energy consumption would represent between 0.11 percent (VLA-JP) and 0.17 percent (VLA-LH_2*) of the available coal. Note that if the C-5B relied on petroleum as the jet fuel source (as does the C-5A at present), then its consumption would be 1.6 percent of that resource;[a] it would thus present a much less favorable picture.

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[a]For simplicity, we are assuming that the entire life-cycle energy requirement is obtained from a single resource. Obviously, this is unlikely in practice, but since fuel energy represents by far the largest single component of the life-cycle total, the approximation seems appropriate for the present discussion.

Nuclear-Fueled Alternatives

Comparisons between the chemical- and nuclear-powered alternatives can also be made that are more meaningful. Consider first the situation if only light water reactors are available for ground-based power generation (i.e., without the advanced-technology liquid metal reactors). For this case, the nuclear airplanes would consume from 2.2 to 2.8 percent of the available resource--more than ten times that of any of the chemical-fueled airplanes when their fuel is synthesized from coal. On the other hand, were the breeder reactor commercially available, the nuclear airplane's consumption would represent only 0.03 to 0.04 percent of the nuclear resource.[a] Under the latter circumstances, the nuclear-powered airplanes appear somewhat more attractive than the other alternatives. Thus, we are faced with the discomforting situation in which the attractiveness of nuclear propulsion hinges on unrelated developments. When, and if, the liquid metal fast breeder reactor will enter commercial service is uncertain [53].[b]

Another view of the resource depletion associated with aircraft nuclear propulsion is also enlightening. Table 18 presents the most recent estimates of domestic uranium resources in terms both of level of assurance (that the reserves exist) and ERDA's index cost [54].

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[a]The astute reader will have observed that the preceding comparisons of the nuclear airplane's life-cycle energy consumption and the magnitude of the resource base are not completely valid. The size of the nuclear resource shown in Fig. 19 represents the energy extracted from the available uranium resource using either of two broad classes of ground-based reactor technology. As we note in Appendix E, how much energy a given reactor provides from a given amount of uranium depends on the type of reactor as well as its specific design. Thus, to complete the picture we must consider the size of the uranium resource base.

[b]Observe that the advent of the breeder reactor does not provide an unlimited source of energy. Breeders simply make it possible to use the otherwise nonfissionable uranium isotope U^{238}. This isotope is more than 100 times more abundant than the fissionable isotope, U^{235}, which fuels the light water reactor. Thus, the introduction of a breeder reactor would increase the size of the nuclear fission resource base, as noted abov , and also allow lower-grade ores to become economically viable (see Appendix E).

Table 18

ESTIMATES OF U.S. URANIUM RESOURCES
(Thousands of tons[a] of U_3O_8)

Increasing Index Costs ($/lb, U_3O_8)[d]		Identified[b]			Potential (Undiscovered)[c]			Totals (Identified & Potential --by Index Cost)
		Demonstrated			Probable	Possible	Speculative	
		Measured	Indicated	Inferred	Known Districts	Productive Provinces	New Provinces	
					Productive Formations		New Formations	
		Decreasing Degree of Assurance						
$8	Economic (1974)	Reserves 280			300	210	30	820
	Not Yet Economic	Reasonably Assured						
$9 to 10	Not Yet Economic	60			160	190	80	490
$10 to 15	Not Yet Economic	180			230	250	100	760
$15 to 30	Not Yet Economic	180			280	710	210	1380
Totals		700			970	1360	420	3450[e,f]
$30 to 100	Unknown	Host Formations Other Than Sandstone, 100 to 500 ppm U_3O_8						?
$100+	Unlikely	Chattanooga Shales, 60 to 80 ppm U_3O_8						~5000
$150+	Unlikely	Chattanooga Shales, 25 to 60 ppm U_3O_8						~8000

SOURCE: Based on [54].

[a]1.1 tons U_3O_8 = 1 metric ton U_3O_8 = 1000 kilograms U_3O_8.

[b]Ores to grades down to approximately 0.12 percent U_3O_8; approximately 95 percent from sandstone host rocks.

[c]Ores to grades down to approximately 0.10 percent U_3O_8, primarily from sandstone host, but including small contributions from other host formations such as veins, conglomerates, and tuffaceous material at grades down to approximately 0.25 percent U_3O_8, where there are sufficient data to judge the possible quantity of uranium.

[d]The index cost is not the average cost of production. And more importantly, *it is not the price* at which uranium will be sold.

[e]This is a new total, approximately 1,200,000 tons U_3O_8 higher than 1-1-74 estimates, a result of the Preliminary National Uranium Resource Evaluation Program (PNURE), started in late 1974.

[f]There are other small domestic sources of uranium: 200,000 metric tons of *depleted* uranium tails, available to stock LMFBRs (sufficient for at least 2000 1000-MWe LMFBRs); 20,000 tons of U_3O_8 recoverable from copper ore leach solutions between now and year 2000; 70,000 tons of U_3O_8 recoverable from phosphoric acid made from Florida phosphate rock between now and year 2000; 2000-3000 tons U_3O_8 per year by year 2000 from lignite gasification assuming 75 percent recovery of U_3O_8 and 20 percent of natural gas demand supplied from lignite. (No production now planned.)

Note that the identified reserves (i.e., both demonstrated and inferred) up to \$30/lb amount to 700,000 tons of U_3O_8 (uranium oxide, or yellowcake).[a] The inclusion of potential reserves increases the total to 3.45 million tons.

In Appendix E, we calculate that the reactor core of each VLA-NUC would require 297 tons of U_3O_8 (269,700 kilograms). A fleet of 224 UE aircraft (258 total aircraft including the pipeline/attrition allowance) would therefore require 76,630 tons of yellowcake to fuel all of its reactors. Referring to Table 18, this amount of yellowcake corresponds to 10.9 percent of the identified reserves and 2.2 percent of the total identified *and* potential reserves. In either case, nuclear power for airplanes promises to be an enormous investment of available U.S. uranium resources. Of course, as we describe in Appendix E, not all of the uranium in the reactor core is consumed. Indeed, most of the energy content of the original core is available for reprocessing after 10,000 hours of reactor operation. Nonetheless, the uranium is unavailable for other uses while it resides in the aircraft reactor.

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[a]The index cost of uranium extracted today is about at the \$15/lb level.

VII. THE STRATEGIC AIRLIFT MISSION

This section describes the relative attractiveness of the seven alternative airplanes for the strategic airlift role. A detailed comparison is made of the cost-effectiveness and energy-effectiveness of the alternatives in six different mission scenarios.

GENERAL APPROACH

These strategic airlift mission analyses were accomplished with the aid of an airlift simulation model. What follows explains our approach in general terms. (Some detailed analytical aspects of the airlift simulation are discussed in Appendix F.)

Units Deployed

The United States Army is presently organized into thirteen active divisons. Of these, four and a third are located in Europe and one in Korea. The remaining divisions, located in the United States, are:

- 1st Mechanized Infantry Division[a]
- 2d Armored Division
- 4th Mechanized Infantry Division
- TRICAP Division[b]
- 82d Airborne Division
- 9th Infantry Division
- 25th Infantry Division
- 101st Airmobile Division

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[a] One-third of this division is in Europe.

[b] Currently being restructured as the 1st Cavalry Division and the Air Cavalry Combat Brigade. We have treated the TRICAP as a standard armored division [55].

The first three of the listed divisions have essentially a complete set of duplicate unit equipment pre-positioned in the NATO theater. (In the event of a major NATO reinforcement, troops in these three divisions, plus a small amount of equipment, would be the first units deployed to Europe. The unit equipment left behind in the United States would subsequently be manned by reservists.)

Our strategic airlift mission analyses consisted of simulating the deployment of these eight divisions and their associated initial support increments (ISI).[a] In the simulation, the unit equipment weights for the divisions and the ISIs (See Table 19) were the actual weights at the beginning of 1974 [55]. Table 19 includes only items currently classified as air-transportable (i.e., items that can be carried by a C-5A). Note that the weights for the three pre-positioned divisions are much smaller than the others; for this reason, the totals in Table 19 are valid only for a NATO deployment.

From Table 19, the total cargo for the eight divisions that must be deployed is about 423,000 tons.[b] Existing NATO contingency plans

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[a]Initial support increment is a planning concept used to represent the aggregate of units required to support a division in combat for a short period of time after deployment. As such, ISIs are made up of the active and reserve units that are required to deploy with the division. Each type of division has a notional ISI (i.e., a list of units which operational planners believe can support the division in a wide variety of contingencies). We have used the notional ISIs as described by the Army in 1974 but included only those units actually in existence at that time (including active and reserve units) [54]. The makeup of the ISIs was assumed to be invariant for all of the deployment scenarios examined in this analysis.

[b]During 1975, the Army restructured the composition of the units listed in Table 19. Thus, the September 1975 TOEs indicate a total air-transportable weight of some 477,000 tons. This augmented Army reflects recent changes in the support units, etc. One of the important aspects of the augmented Army is that almost 38 percent (by weight) of the total is outsized equipment; for the weights in Table 19, less than 31 percent is outsized. Fortunately, this large difference has little bearing on the present work since all of the alternatives have an outsize capability. It could be critical, however, if nonoutsize cargo airplanes were under consideration.

Table 19

ARMY UNIT EQUIPMENT WEIGHTS (AIR-TRANSPORTABLE ONLY)
(Tons)

Unit	Division Weight	ISI Weight
1st Mechanized Infantry	3,007[a]	37,223[b]
2d Armored	6,357[a]	41,049
4th Mechanized Infantry	6,689[a]	36,682
TRICAP (1st Cavalry)	44,941	35,394
82d Airborne	10,119	38,374
9th Infantry	26,904	37,350
25th Infantry	26,904	29,446
101st Airmobile	11,057	31,762
Total	135,978	287,280

SOURCE: U.S. Army Tables of Organization Equipment (TOE), March 1974 [54].

[a]Excluding pre-positioned equipment.

[b]Most equipment of the ISIs for the 1st Mechanized Infantry Division has recently also been pre-positioned in Europe.

call for a substantial fraction of this unit equipment to be transported by sealift [56]. For the present study, however, we assume that all deployment requirements are to be met by airlift. For the NATO mission scenarios, all units shown in Table 19 are deployed. In the other scenarios, only the last five divisions listed and their ISIs (i.e., everything except the pre-positioned divisions and their ISIs) are assumed to participate in the deployment.

In the deployment simulations, the unit equipment is moved from an APOE (aerial port of embarkation) within one day's march of the unit's actual location in the United States to the assumed APOD (aerial port of debarkation) in the deployment area. (Details are included in Appendix F.)

Before describing the mission scenarios that have been examined, we emphasize that deployments of the units listed in Table 19 should be regarded as illustrative only. The Army has recently proposed a major reorganization that would increase active strength to 16 divisions by 1983. The unit equipment weight of these 16 divisions and their ISIs might then exceed 600,000 tons [55]. Nonetheless, since they reflect the deployment requirements for a representative mix of actual Army units, the results of the present study should provide a meaningful basis for judging the alternative airplanes.

Deployment Mission Scenarios

The deployment scenarios examined in this work are intended to be representative of the different kinds of missions that might be flown if a worldwide deployment capability--without reliance on foreign bases --were a U.S. military objective.

NATO Deployment. The ability of the United States to reinforce the NATO theater rapidly in the event of a potential general war in Europe is a virtual cornerstone of U.S. foreign policy [49,57]. In recent months, numerous studies have examined near-term means for enhancing our ability to airlift troops and equipment to NATO. All such studies have presumed that fuel is available in Europe for the airlifter's return leg. We too analyzed this scenario (but with an obviously longer-term perspective). In this scenario, all aircraft are presumed to fly range missions, with Frankfurt, West Germany, the assumed APOD.[a] Returning airlifters are routed through England to minimize the amount of fuel being removed from the continent.

We also analyzed a NATO deployment scenario in which all airlifters fly radius missions from the continental United States (CONUS). That is, fuel is assumed to be either unavailable or at a very high premium in Europe. It is difficult to assess the reasonableness and importance of this scenario. One view is that the U.S. airlift fleet (including all of the recently advanced enhancement options [49,57]) would daily

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[a] Actually, a number of points would serve as APODs. The use of Frankfurt only, however, greatly simplifies the analysis--and with little loss of realism.

require about three times as much fuel for the return leg as the es i-mated daily requirement of all U.S. combat aircraft at the start of hostilities [58]. At the other extreme, it is held that the airlifter's daily requirement is only about two percent of the jet fuel likely to be on hand (in storage) in West Germany and the United Kingdom alone [58]. If the maximum amount of jet fuel that could be refined from the crude oil on hand is included, the daily requirement could be less than 0.1 percent [59,60].

Clearly, much depends on the nature of the conflict. If hostilities are not yet under way, then the radius mission may be of little interest. However, one of the principal arguments for enhanced airlift capability is the increased threat to sea lanes. If sea lanes are interdicted, we believe it logical to assume that Europe's fuel supply and distribution system is also vulnerable either to air strikes or sabotage. For these reasons, including the radius mission in the NATO deployment scenarios appears reasonable.

Middle East Missions. Both range and radius mission scenarios for the deployment of Army units to the Middle East have also been analyzed. These scenarios reflect the mission requirements of airlifting equipment to the eastern Mediterranean area. The APOD is assumed to be Tehran, Iran, and this makes the mission one of the longest range of any that are likely to be of interest. (The flight distance to Tehran is approximately 700 n mi greater than that to Tel Aviv, Israel.)

Airlift missions to the Middle East are of particular interest because of the potentially extreme flight distances. If no en route refueling bases are available and overflight rights are restricted, the flight distance from Dover AFB, Del., to Tehran is about 6100 n mi, assuming overflights of Turkey. If no overflights are permitted, then the shortest route from CONUS to Tehran is through Andersen AFB, Guam. The Andersen-Tehran leg is approximately 6700 n mi without overflights.

Fuel availability may be a more acute issue in these scenarios than in the NATO ones. In Section I, we observed that the fuel removed from Israel exceeded (by weight) the equipment delivered during the 1973 airlift--even with the Azores available for in-flight refueling. Furthermore, depending on the nature of the conflict, fuel distribution

and storage facilities may be quite vulnerable. Under these circumstances, including radius mission profiles seems particularly appropriate.

Of course, our choice of Tehran as the APOD is only intended to provide an illustrative example of this type of deployment mission. Furthermore, the analytical results are equally valid when interpreted in terms of resupplying equipment by airlift instead of the deploying of actual Army units.

Far East Missions. The last two scenarios (again, for either range or radius mission profiles) are deployments to the Far East. These scenarios were included as representative of long range/radius missions in which U.S.-owned bases are available for refueling. Our specific example is a deployment to Kuala Lumpur in Malaysia. For the Far East deployment scenarios, the importance of examining radius mission profiles should be unquestion .

A candidate scenario that has not been examined in the present work is the reinforcement of Korea. However, the requirements of such a deployment are substantially less severe than those of either the Middle East or Far East scenarios. For example, Seoul, Korea, is only about 3500 n mi from Elmendorf AFB, Alaska. Alternatively, the Seoul-McChord AFB, Wash., flight distance is about 4500 n mi. (In both cases, we have assumed no overflights of non-U.S. territory.) Accordingly, deployments to South Korea have requirements that are somewhat more severe than the NATO deployments but substantially less than those of the Middle East scenarios.

Routes and Bases

The strategic airlift mission analyses described in this report are premised on the use of bases in the United States or on U.S.-owned territory only. The locations of eight bases of particular importance to the airlift missions are shown in Fig. 20.[a] (These eight bases were

[a]The fuel supply systems (e.g., storage tanks, pipelines, etc.) for the chemical fuels were sized to provide the fuel requirements of these eight bases when supporting airlift operations. As such, the unit fuel costs and the energy considerations discussed in Sections V and VI are the average values for supply systems to each of these bases [19].

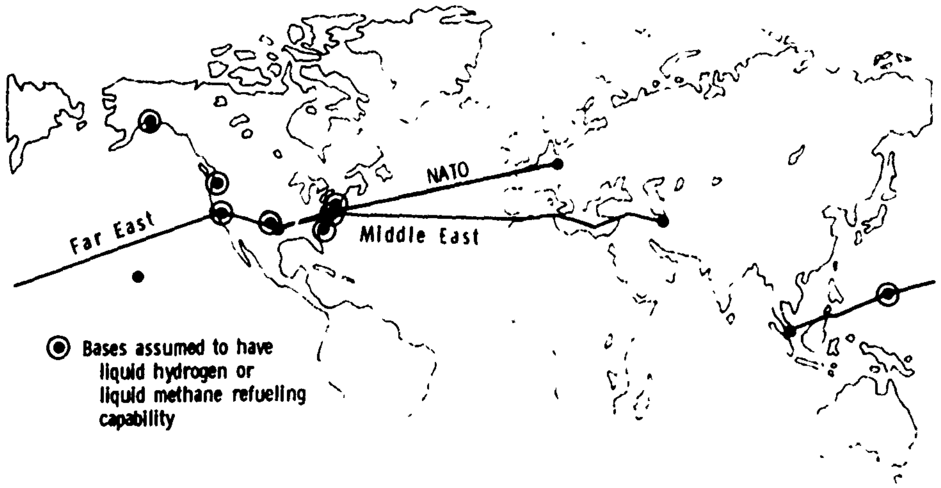

Fig. 20 — Typical deployment routes

originally identified as the minimum number needed to provide, at least initially, the capability for refueling the cryogenic alternatives. With this initial basing structure, the cryogenic-fueled airplanes could provide a worldwide airlift capability.) For the range-mission scenarios, we have assumed that the liquid-methane and liquid-hydrogen-fueled alternatives have a dual-fuel system. Thus, they can fly return legs using JP, and the availability of cryogenic fuel at the APOD is not a requirement. If a dual-fuel system is not feasible, the cryogenic airplanes might be restricted to radius missions only. The implications of such a restriction will be brought out in the summary discussion of the airlift analysis results.

Typical deployment routes are also illustrated in Fig. 20. In this particular example, Fort Hood, Texas, serves as an example of an Army equipment location. The APOE is Robert Gray Army Airfield (located at Fort Hood). The routes shown on this chart are typical of a chemical-fueled VLA flying a radius mission. For example, in the

NATO deployment, the VLA stops for a ground refuel at Dover Air Force Base, Del., and then proceeds to fly a radius mission to the APOD (Frankfurt). The VLA refuels at Dover on the return leg and then flies to Robert Gray where it is loaded for the next trip. (The cryogenic-fueled airplanes would not require refueling at Robert Gray AAF).

On the other hand, when deploying to the Middle East using a radius mission profile, the chemical-fueled VLAs would require an in-flight refueling. In the case of the VLA-JP, a single outbound refueling is required (from Dover)--the refueling taking place (using buddy rules) just before the airlifter enters the Mediterranean. The C-5B, on the other hand, would require both an outbound and an inbound in-flight refueling. (Even with the two refuelings, however, it has only about a 40,000-lb payload capability on this 6100 n mi radius mission.)

Interestingly, the nuclear airplanes' routes for the NATO and Middle East scenarios would be similar to those shown in Fig. 20 if U.S. overflights with the reactor in operation were forbidden. The only exception is the NATO range mission in which the inbound refueling stop in England (assumed to occur at Mildenhall RAF) can be eliminated.

The importance of Andersen AFB, Guam, to the Far East deployment missions should be apparent from Fig. 20 (and Fig. 5 in Section II). If Andersen were unavailable as a refueling base because of hostile action, several alternatives exist. Of the numerous islands in the vicinity of Guam, only Wake Island (approximately 1300 n mi to the northeast) would appear suitable. If all potential refueling stops in the western Pacific are discounted, then Hickam AFB, Hawaii, could be employed. Using Hickam, the flight distances for the Far East deployments would be similar to those of the Middle East missions from eastern CONUS bases. Thus, as long as bases in Hawaii are assured, worldwide coverage will be provided by the chemical-fueled very large airplanes. One of the most attractive aspects of the nuclear airplanes is the elimination of the need for at least one refueling base in the western Pacific.

Airlift Fleet Size

A measure of capability in the strategic airlift mission is the number of days required to deploy the Army units of interest (i.e., the closure time). Since the weights of the units are assumed to be constant, an equivalent measure of capability (or effectiveness) is the average tons per day deployed (i.e., the total weight of the units divided by the closure time). The airlift fleets can thus be sized to provide a desired closure time for a particular mission scenario.

Figure 21 provides some typical examples of this measure of capability. Depicted are the results for the deployment of the eight Army divisions and their ISIs to NATO--assuming radius missions are being flown.

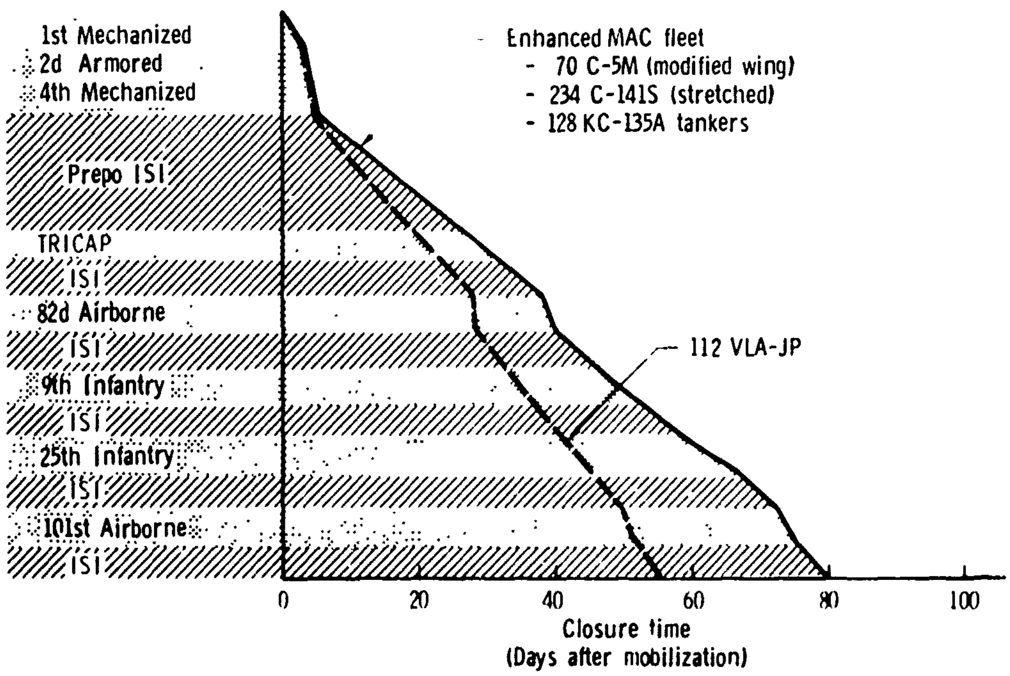

Fig.21 — Capability examples for the NATO-radius mission

The solid line depicts the closure time for a deployment using the enhanced MAC fleet alluded to earlier. This fleet consists of 70 UE C-5As (with the Option H wing), 234 UE stretched C-141s, and is supplemented by 128 KC-135A tankers (which permit the airlifters to fly radius missions). In this instance, approximately 80 days are required to airlift the Army units of interest. Also shown are the results for a fleet of 112 UE VLA-JPs; using only these airplanes reduces the closure time to about 55 days.

The closure times presented in Fig. 21 have been estimated by a moderately detailed simulation of airlift deployment. The simulation includes such factors as ground times for loading, unloading, and refueling; adjustment of flight distances for average winds; and the airlifter's range-payload characteristics and cargo compartment dimensions. Two inherent analytical assumptions are particularly important, and will be summarized below. (They are discussed in detail in Appendix F.)

For the present work, we have made substantial modifications to an existing Rand deployment model recently used to investigate alternative near-term means of enhancing strategic airlift in the context of the NATO contingency [61]. An important implicit assumption in this model is that, for each division or support unit originating at a given APOE, all sorties flown by a particular airplane type will reflect some average aircraft payload. For a given scenario, the average loading is determined as the smaller of the volume-limited average payload for equipment corresponding to each unit type, or the maximum payload capability of the airplane for the wind-adjusted critical leg of interest (see Appendix F). In our present work, we used average loadings that are comparable to those provided in the USAF Airlift Planning Factors manual (AFM 76-2) for the C-5A and C-141A airplanes [3]. The alternative to making such an assumption is to utilize a detailed loading simulation model as discussed in Appendix F. Although such a model presently exists at Rand [62], it is quite expensive to use and applying it in the present work would have been prohibitively costly because of the large number of cases that would need to be analyzed.

Our second important assumption is that all unit equipment aircraft maintain the same operational readiness rate. Specifically, we have used an OR rate of 0.58; this corresponds to the OR rate that the C-141A aircraft must maintain to yield an average utilization rate of 10 hours per day in the NATO deployment scenario when flying range missions. Both of these assumptions are consistent with our objective of comparing alternative airplanes in the strategic airlift role. However, when examining the absolute value of any of the deployment parameters presented (e.g., comparing airlift closure time with closure time for sealift), caution should be exercised.

We have chosen to determine the fleet size for each of the alternative airplanes by requiring that each provide approximately equal capability in the NATO reinforcement scenario. Indeed, the results depicted in Fig. 21 for 112 UE VLA-JP indicate the capability to close the eight divisions in approximately eight weeks when flying radius missions to NATO. In 1974, Secretary of Defense James Schlesinger suggested as a goal a closure rate of one division (plus support unit) per week [6]. Use of this measure of desired capability for the other alternatives yields the following fleet sizes: 112 UE for the VLA-JP, VLA-LCH_4, and VLA-LH_2; 96 UE for the VLA-LH_2*; and 225 UE for the C-5B.[a] If we assume that the nuclear airplanes are not permitted to overfly CONUS with the reactor in operation, then 112 UE VLA-NUCs are required or 194 UE VLA-NUC*s. If overflying the United States with reactors in operation were permitted, the same number of UE nuclear airplanes would show a substantially greater capability. (We have analyzed both of these situations and will discuss this point at greater length subsequently.)

Cost-Effectiveness and Energy-Effectiveness Definitions

The preceding discussion indicated how fleet sizes for each of the alternatives were fixed to provide approximately equal capabilities

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[a]The C-5B fleet has been sized to close the eight divisions in eight weeks when all C-5Bs fly range missions (i.e., the design mission profile for the C-5B). By coincidence, 225 UE C-5Bs provide about the same capability for the radius mission as the proposed enhanced MAC (including the 128 KC-135A tankers).

for the NATO radius mission. The fixed fleet size determines the life-cycle costs and life-cycle energy consumption of each of the alternatives. (Indeed, the examples presented in Sections V and VI for the design-point VLAs all presumed 112 UE aircraft.)

If the same number of UE airplanes are applied to some other deployment mission scenario, each of the alternative airplane fleets will provide different levels of capabilities.[a] Consequently, to facilitate comparing the alternative airplanes, measures of cost-effectiveness and energy-effectiveness must be developed.

The following definitions of cost-effectiveness and energy-effectiveness are offered for the strategic airlift mission.

- *Cost-effectiveness:*

$$\text{Life-cycle cost} \div \left(\frac{\text{Net tonnage deployed}}{\text{Closure days}}\right)$$

- *Energy-effectiveness:*

$$\text{Life-cycle energy consumption} \div \left(\frac{\text{Net tonnage deployed}}{\text{Closure days}}\right)$$

The measure of effectiveness is the average tons per day being deployed. However, different definitions of net tonnage deployed have been used for the range and radius mission scenarios.

Recall that for the range missions, fuel was assumed to be available at the destination for the return leg. This implies that the fuel being removed from the theater is considerably less important than the equipment being delivered. Hence, for the range mission we define the net tonnage deployed as the total equipment tonnage plus the total troop tonnage that has been moved.

On the other hand, for the radius mission, fuel availability at the destination is assumed to be a critical issue. Thus, the definition of net tonnage deployed was modified to be the equipment tonnage plus the troop tonnage less the total tons of fuel that must be removed from

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[a]This phenomenon is largely a result of the differences in range-payload characteristics described in Section IV.

the destination (presuming that all airplanes can use JP) for the return flight. The principal reason for defining effectiveness in this fashion was the C-5B's limited ability to perform the Middle East radius mission. That is, realistic results can only be obtained if the C-5B is allowed to take on some fuel at the APOD. In many cases, particularly when carrying volume-limited payloads, the very large airplanes have the capability to bring excess fuel (JP) into the destination. When this occurs, they receive an effectiveness bonus (usually quite small), since the fuel tonnage removed is negative. That is, the net fuel balance can be either positive (i.e., some fuel brought into the APOD) or negative. Note, however, that in all missions analyzed, our ground rule constraints require that the closure days be minimized rather than that the net tonnage deployed per day be maximized.[a]

To illustrate these definitions, detailed results for the NATO radius mission are presented in Table 20. Each column represents one of the seven alternative airplanes; for purposes of comparison, a column for the enhanced MAC fleet is also included. For each alternative, the parameters shown include operational characteristics of the airlift fleet, the life-cycle costs in billions of 1975 dollars,

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[a]This definition of effectiveness essentially equates a pound of payload brought into the APOD with a pound of fuel removed. Consideration of a somewhat different (and more complex) operational concept for radius missions can also lead to this definition. Specifically, if we assume that fuel storage and transfer facilities are available at the APOD, and that the vulnerability of these facilities is not in question, then the deployment could be managed as follows. The payload of some sorties will be volume-limited; on these, fuel weight amounting to the excess payload capacity can be off-loaded at the APOD and placed in storage. Other sorties, in which the payload weight would normally be constrained by the radius capability of the airplane, could carry an increased payload into the APOD and subsequently withdraw sufficient fuel from storage to complete the return leg. If properly managed, this operational concept could yield a net fuel balance of zero at the end of the deployment. Under such circumstances, the average tons per day being moved would be approximately the same as that derived from the original definition.

Table 20

DETAILS OF THE STRATEGIC AIRLIFT ANALYSIS FOR THE NATO RADIUS MISSION

Scenario Parameter	C-5M/ C-141S (KC-135)	C-5B	VLA-JP	VLA-LCH$_4$	VLA-LH$_2$	VLA-NUC	VLA-LH$_2$*	VLA-NUC*
Operational								
UE transports	70/234	157	112	112	112	112	96	194
UE tankers	(128)	68	0	0	0	0	0	0
OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	10.4	10.4	10.5	10.5	10.5	11.8	10.5	11.8
Costs (billions 1975 $)								
Acquisition	-	8.5	15.5	16.5	13.6	32.1	15.1	34.8
20 year O&S	-	18.0	16.4	18.8	21.4	24.6	22.5	30.6
Energy (Quads)								
Aircraft manufacture	-	0.16	0.29	0.31	0.25	0.65	0.28	0.74
20 years' fuel	-	2.42	1.84	2.20	2.63	5.25	2.82	6.63
Capability								
Closure days	80	79	55	55	55	44	53	44
Cargo/troops deployed (kilotons)	423/30	423/30	423/30	423/30	423/30	423/30	423/30	423/30
Net fuel balance (kilotons)	43.4	40.1	48.1	51.0	34.0	42.5	53.4	110.8
Sorties flown	25,063	11,537	2,832	2,832	2,832	2,832	2,334	4,904
Cost-Effectiveness ($ bil/kiloton/day)	-	4.24	3.50	3.85	3.95	5.04	3.94	5.10
Energy-Effectiveness) (Quads/kiloton/day)	-	0.413	0.234	0.274	0.325	0.524	0.324	0.576

the life-cycle energy consumption in Quads, the capability as measured in the ways described earlier, and finally the cost-effectiveness and energy-effectiveness.

Consider first the operational characteristics. All of the VLAs can fly this particular mission without tanker support. However, 68 of the available 225 UE C-5B aircraft must serve in the tanker role.[a] In the case of the enhanced MAC fleet, 128 KC-135As are required, as noted earlier. Although all airplanes are assumed to maintain the same OR rate, the UTE rate varies markedly.[b] Specifically, the less time that a UE transport must spend on the ground (for refueling, etc.), the higher the UTE rate. In this example, because we assume that both nuclear airplanes are permitted to overfly the United States with reactors operating, they have the highest UTE rate. Although this is a tenuous assumption, all of the results that follow are based on that premise. (Our reasoning on this will be made clear shortly.)

Shown next are life-cycle costs. These have been separated into system-acquisition costs and the 20-year operating and support costs. The O&S costs are based on an average UTE rate of two hours per day per aircraft, a UTE rate that is approximately the minimum peacetime flying schedule for airplanes of this type. (In Section VIII, we will discuss O&S costs for much higher UTE rates.)

The life-cycle energy consumption characteristics are similarly broken down, into consumption related to system acquisition and total energy consumption attributable to a 20-year fuel supply.

The measures of capability are shown next. These include the closure days for this deployment scenario, the total tonnage of cargo and

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[a] Determining the split between tankers and airlifters is discussed in Appendix F.

[b] One alternative to assuming a constant OR rate is to assume that all airplanes participating in the deployment maintain the same average UTE rate. We have duplicated the entire strategic airlift analysis assuming that all airplanes average 10 flying hours per day. None of the results changes substantially if the analysis is performed in this fashion. The constant OR rate results are presented because we believe them to be better approximations of reality.

troops that have been airlifted, the net fuel balance (at the APOD), and finally the total number of sorties flown. A positive fuel balance indicates that that quantity of JP has been delivered to the APOD, along with the equipment and troops.[a] The enhanced MAC fleet and the C-5B require the greatest time to close--about 80 days. All of the chemical-fueled VLAs require about 55 days. The nuclear airplanes, since they are overflying CONUS with their reactors powered-up, reduce closure time substantially--to about 44 days.[b] Note that the total cargo and troop tonnage deployed is identical in all cases.

The bottom two items on Table 20 show cost-effectiveness and energy-effectiveness. For this particular mission, the VLA-JP is the most attractive in terms of cost-effectiveness. The least cost-effective alternatives are the nuclear airplanes. The VLA-JP is also the most energy-effective and the nuclear airplanes are, again, the least attractive.

This analysis was performed for each of the six mission scenarios described earlier. (Similar detailed results for the other five mission scenarios are presented in Appendix F.) The cost-effectiveness and energy-effectiveness results for these analyses are summarized below.

SUMMARY COMPARISON

Table 21 summarizes the relative cost-effectiveness and energy-effectiveness of each of the seven alternative airplanes for each of the six strategic airlift mission scenarios that we have investigated. For simplicity, we have normalized these results to the cost-effectiveness and energy-effectiveness of the C-5B when flying the NATO range mission.

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[a] A negative fuel balance would indicate that JP is being removed from the APOD for the return trip.

[b] Some of the fuel delivered by the nuclear airplanes might be retained to increase their emergency recovery range on the return leg. The fuel balance shown in Table 20 allows only an 850 n mi recovery range for the nuclear alternatives on the return leg.

Table 21

SUMMARY OF RELATIVE COST AND ENERGY EFFECTIVENESS FOR STRATEGIC AIRLIFT MISSIONS

Airlift Mission	C-5B	VLA-JP	VLA-LCH$_4$	VLA-LH$_2$	VLA-NUC	VLA-LH$_2^*$	VLA-NUC*
Relative cost							
NATO range	1.00	1.06	1.24	1.28	1.63	1.35	1.92
NATO radius	1.23	1.01	1.12	1.14	1.46	1.14	1.48
Middle East range	1.84	1.65	1.86	1.88	2.57	1.95	3.02
Middle East radius	18.52	2.67	2.38	2.32	2.32	2.33	2.31
Far East range	1.84	1.95	2.25	2.23	3.09	2.33	3.63
Far East radius	1.53	1.34	1.56	1.86	2.75	1.87	2.79
Relative energy							
NATO range	1.00	0.73	0.90	1.08	1.74	1.14	2.22
NATO radius	1.23	0.70	0.82	0.97	1.56	0.97	1.71
Middle East range	1.84	1.13	1.36	1.59	2.74	1.64	3.50
Middle East radius	18.52	1.83	1.74	1.96	2.47	1.97	2.67
Far East range	1.84	1.33	1.64	1.88	3.30	1.97	4.20
Far East radius	1.53	0.92	1.14	1.56	2.93	1.59	3.22

Most attractive Intermediate Least attractive

Consider first the relative costs for the NATO range mission. None of the alternatives is more cost-effective than the C-5B; however, in terms of energy, the C-5B appears considerably less attractive. For the NATO radius mission, on the other hand, the relative cost of all the chemical-fueled VLAs is less than that of the C-5B. It is interesting to note that the mission profile flown on the NATO range mission approximately corresponds to the C-5B's design point, whereas the VLA's design point corresponds essentially to the profile for the NATO radius mission. The remaining missions provide insights into the off-design performance of all the alternative airplanes.

The intent of the summary presented in Table 21 is twofold: first, to show how the relative cost and relative energy of the VLAs and C-5B change for the different mission scenarios and, second and perhaps more important, to aid in the selection of the alternative airplane that is most attractive from an overall viewpoint. To do this, however, one must attach a relative importance to each of the six mission scenarios, for some of the scenarios may be far more important than others.

To help select the alternative that is most attractive overall, we have indicated the relative rankings of the alternatives in each scenario. For example, in the NATO range mission, the C-5B and the VLA-JP are clearly the most cost-effective, the two nuclear airplanes the least cost-effective, and the cryogenic-fueled airplanes in the middle range. This scheme has been repeated for both relative cost and relative energy in each mission scenario. Overall, the VLA-JP appears to be the most attractive of the alternatives. However, careful consideration shows that the VLA-JP does not overwhelmingly dominate the C-5B in cost-effectiveness--particularly if the Middle East radius scenario is discounted. (In many scenarios, the closure time of the C-5B is substantially longer. However, closure times could be equalized in any scenario by procuring additional C-5Bs. Under such circumstances, the relative cost-effectiveness would not be significantly altered.) None of the other alternatives reasonably challenges the superiority of the VLA-JP.

We have defined effectiveness as average tons per day deployed; a general meaning can therefore be attached to these results. Rather than only representing the deployment of the specific Army divisions examined, they have equal validity for determining expected average capability in airlifts of Army equipment for other purposes (e.g., resupply missions, deployments of a more modest scale, etc.). This assumes, of course, that the makeup of the divisions and support units is typical of what would be moved in other types of contingencies.

In summary, then, we conclude that for the strategic airlift mission, neither the cryogenic-fueled alternatives[a] nor the nuclear alternatives[b] promise substantial benefits in cost-effectiveness or energy-effectiveness when compared with the C-5B or the VLA-JP. The choice between the C-5B and the VLA-JP is dependent on the relative importance attached to the various mission scenarios as well as the relative importance of cost and of energy consumption.

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[a]Remember that the range mission results for the cryogenic-fueled alternatives assume that either: (1) cryogenic fuel is available at the APOD for the return flight, or (2) the airplanes are capable of making the return flight on JP. There are no insurmountable technological problems associated with a dual-fuel system for the liquid methane or liquid hydrogen airplanes [63]. Of course, when operating on JP, the airplane's performance will be substantially degraded, but it should still be sufficient to perform the zero-payload return flights. However, if neither condition is met, then for each deployment destination, the radius mission results for the cryogenic-fueled alternatives must be compared with the corresponding range mission results for the other alternatives. Because of differences in the definition of the effectiveness metric, this can only be accomplished by referring to the detailed results presented in Appendix F.

[b]The reader is also reminded that the results depicted in Table 21 presume that the nuclear airplanes are permitted to overfly the United States with their reactors in operation. If such overflights are forbidden, then the nuclear airplanes would appear even less attractive.

VIII. THE STATION-KEEPING MISSIONS

In Section II, six broadly defined mission areas were identified as candidate applications of very large airplanes. We have given our analysis of two of these mission roles--airlifter and tanker (when participating in strategic airlift operations). We term the remaining four mission areas station-keeping missions.[a] They are:

- Missile launcher
- Tactical battle platform
- Maritime air cruiser
- Command, control, and communications platform

Our strategic airlift mission analyses included detailed deployment simulations; these were possible because mission requirements were relatively well defined. The station-keeping mission requirements are much less definitive, consequently they have been analyzed in a generic sense. That is, the required mission profile for any of the station-keeping missions will be characterized by the distance from the base to the station-keeping point (i.e., the station radius) and the time the airplane remains on-station (i.e, the time-on-station). Thus, by parametrically considering several combinations of station radii and times-on-station, the performance of each of the alternative airplanes in such missions can be explored. *(Although insights can thereby be gained into the suitability of each alternative airplane as a platform in these several applications, little can be said about the utility of the various station-keeping missions themselves.)*

GENERAL APPROACH

Below we discuss the rationale for examining the station-keeping missions in a generic sense. Also described is how life-cycle cost

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[a]More detailed descriptions of each mission area were presented in Section II.

and life-cycle energy consumption estimates, based on the station-keeping fleet size and operational readiness rate, were generated for each alternative. By then developing an effectiveness metric that is representative of on-station performance, the cost-effectiveness and energy-effectiveness of each alternative can be expressed for any station radius and time-on-station.

Station Radii of Interest

The station-keeping missions are discussed below in terms of the station radius appropriate to each mission. In each instance, the time-on-station is dependent on the requirements of the specific missions.

Figure 22 displays the contours (as solid lines) of several representative station radii; each station radius contour consists of

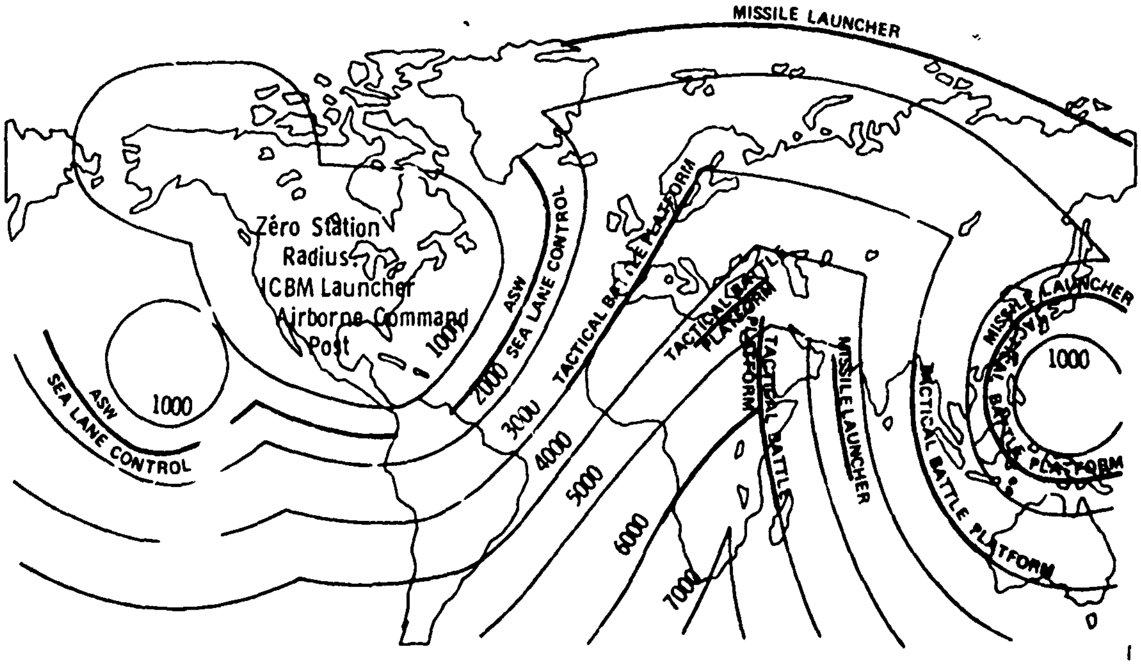


Fig. 22 — Representative station radii (in nmi) of potential station-keeping missions

the set of points that are approximately equidistant from bases in CONUS, or from Elmendorf AFB (Alaska), Hickam AFB (Hawaii), and Andersen AFB (Guam).

Consider first a zero station radius (i.e., the aircraft remains in the vicinity of the originating base). This is a profile applicable to the airborne command post concept and the ICBM launcher but of little interest to the other candidate missions.

Moving outward from CONUS, consider a station radius of 1500 n mi. In the mid-Atlantic area, this seems to be a representative radius for maritime air cruiser applications (either ASW or sea-lane control missions). Similar maritime missions might be performed by standing about 1500 n mi off either western CONUS or Hickam. On the far right-hand side of Fig. 22, a 1500 n mi station radius from Andersen AFB is representative of the profile that might be employed by an air-launched cruise missile platform for targets in the Far East. Similarly, this station radius is applicable to a tactical battle platform for operations in the Far East or Southeast Asia. Finally, note that the 1500 n mi contour on the top of Fig. 22 is also applicable to missile launchers (of either ICBMs or ALCMs) when northern entry into the Soviet Union is desired.

The next station radius highlighted is 3000 n mi. In the North Atlantic, this is the appropriate radius for tactical battle platform operations in the NATO theater. It also provides coverage for tactical battle platform operations in the more distant parts of Southeast Asia--again using Andersen as the originating base for the station-keepers.

A station radius of 4500 n mi appears applicable to either a tactical battle platform for Middle East operations or a missile launcher that provides opportunity for southern entry into the Soviet Union--either from the Mediterranean area or from west of the Indian subcontinent.

Lastly, the 6000 n mi station radius would be useful for tactical battle platform operations in the Persian Gulf area or, perhaps, for operations in the southern part of Africa.

In our analysis of the station-keeping missions, we have explicitly considered each of the aforementioned station radii (zero, 1500, 3000, 4500, and 6000 n mi); these radii, based on our preceding discussion, represent the likely spectrum of requirements for the various station-keeping missions. It is our belief that station radii greater than 7000 n mi are of little practical interest; Fig. 22 is offered as the principal evidence for this assertion.[a]

Our analytical approach for comparing the alternatives is to examine their performance at the likely extremes of the required time-on-station at each of those selected station radii. By doing so, we capture all of the mission parameter space of interest for any of the station-keeping missions.

Station-Keeping Fleet Size

To size the station-keeping fleet, we have assumed that the airplanes used in these missions represent a second buy of as many airplanes as required for the airlift mission. That is, the total number of UE aircraft procured (airlifters/tankers plus station-keepers[b]) is assumed to be equal to exactly twice the number procured for the strategic airlift mission. This would result in acquisition costs lower than the costs observed in the strategic airlift analysis, since there would be no RDT&E costs associated with the acquisition program. In addition, the learning-curve effect would significantly reduce the average unit flyaway cost of the station-keepers.

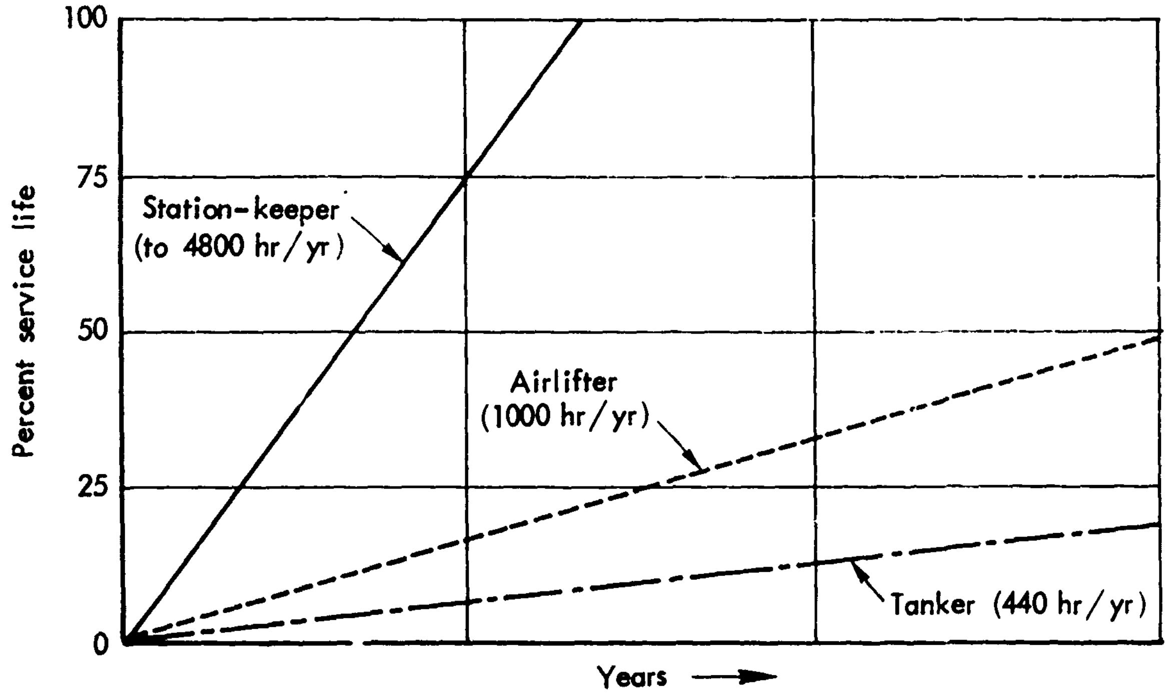
[a]Clearly, not all potential station-keeping missions are shown in Fig. 22. For example, one application presently being discussed is the so-called "strategic reserve mission." The objective is to assure the survivability of a reserve ICBM force by maintaining the weapons on an airborne alert. As such, the carriers might operate from within a few hundred miles of CONUS out to several thousand miles (e.g., in the South Pacific). The intent of Fig. 22 is merely to broadly associate potential missions with an appropriate station radius.

[b]Just as some of the aircraft procured as airlifters must serve as tankers in some airlift mission scenarios, certain station-keeping mission profiles also require that some of the available UE be diverted for tanker service.

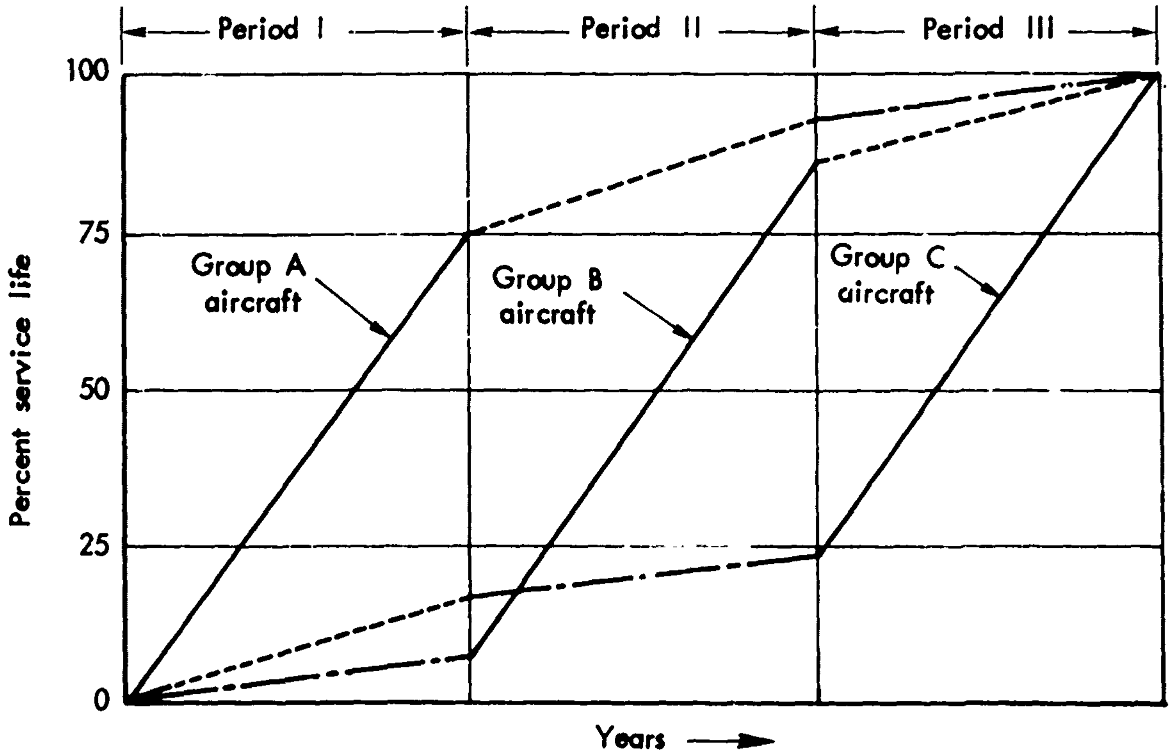
This apparently arbitrary specification of the number of UE in the station-keeping fleet is rooted in an attempt to take advantage of one of the conceptually most attractive aspects of multimission aircraft. As observed in the preceding sections, airlifters and tankers characteristically maintain low peacetime UTE rates (e.g., one to three hours per day on the average). On the other hand, as will be indicated in the subsequent discussion, station-keepers maintaining a maximum airborne alert could average from 13 to 14 flying hours per day. Consequently, aircraft serving exclusively in the station-keeping role would expend their useful service life much more rapidly than airlifter/tanker aircraft, as illustrated in Fig. 23a. A multimission aircraft could successfully exploit this situation. As demonstrated in Fig. 23b, at the end of time Period I, the Group A aircraft would switch from the station-keeper to the airlift role, the Group C aircraft from the airlifter to the tanker, and Group B aircraft would become station-keepers for Period II. Similar role changes would occur at the beginning of Period III. Thus, by appropriate manipulation of operational roles, all UE aircraft would essentially wear out at about the same time.

Of course, implementing this in practice would be complex. For example, service life depends not only on flying hours but on the kinds of mission profiles flown. Furthermore, additional costs would be incurred in the periodic changeovers of avionics, unique equipment, etc. (Note that the airlifter and station-keeping fleets do not *need* to be the same size; our assumption of equal fleet sizes is somewhat arbitrary, although conceptually the most straightforward.)

In summary, our approach for estimating the life-cycle costs and life-cycle energy consumption of each station-keeping fleet was the following: Acquisition components were determined for the above-specified fleet sizes using the information presented in Appendix D and sections V and VI. Corresponding operating and support components were developed by assuming that the station-keepers were utilized to provide a maximum continuous airborne alert capability for the specified operational readiness rate. For simplicity, all UE aircraft (i.e., both station-keepers and tankers) are assumed to maintain the



(a) Dedicated to a single mission



(b) Typical service-life equalization program

Fig. 23 — Illustrative equalization of service life for multimission aircraft (adapted from Lockheed-Georgia Co. [33])

same OR rate, which was fixed at 0.58. The resulting UTE rates are specific to each alternative and mission profile (i.e., station radius and time-on-station), as will be shown. The O&S costs and energy consumption can be estimated. using the previously presented material, once the UTE rate is known.

Measuring On-Station Performance

Our principal measure of effectiveness for each generic mission profile is the total payload tonnage that can be maintained on-station continuously. In other words, for each station radius and time-on-station, each alternative airplane fleet will have a maximum tonnage that can be maintained on-station; this maximum is achievable for some specific mix of carriers and tankers from the available UE total.[a]

Figure 24 provides some typical examples of the on-station performance that can be expected from the very large airplanes for a 12-hour and a 324-hour minimum time-on-station. Presented are the average payloads maintained continuously on-station as a function of station radius for the VLA-JP and the VLA-NUC alternatives.

First, we should explain why the results depicted in Fig. 24 represent a *minimum* time-on-station rather than a specified *exact* time-on-station. In the case of the chemical-fueled airplanes, as illustrated here for the VLA-JP, a slight irregularity in the symbols with respect to the smoothly faired curves can be observed. The irregularity is partly a consequence of allowing the chemical-fueled airplanes to remain on-station somewhat longer than the specified minimum time. This prevents the airplane's receiving an in-flight refueling while on-station, leaving the station within a short time (whenever the specified time-on-station is achieved), and thus returning to base with fuel tanks that are not nearly empty. Our analysis requires that the airplanes remain on-station for at least the minimum time and receive no additional in-flight refuelings (on-station)

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[a]The details of the analysis, including the determination of the mix between carriers (i.e., aircraft in the station-keeping fleet actually serving in the station-keeping role) and tankers, are included in Appendix G.

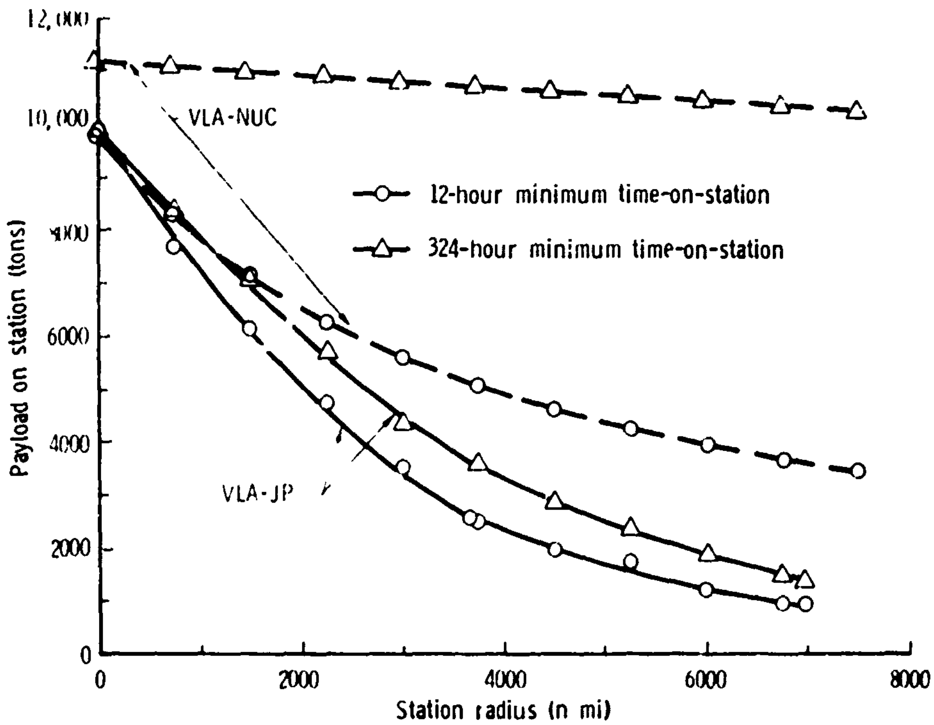

Fig. 24 — Typical VLA on-station performance for 112 UE aircraft

after that time. Thus, the symbols for the chemical-fueled airplane represent actual station-keeping times of between 12 and 20 hours. We think this is wholly consistent with the way such airplanes would be employed in practice--at least, in peacetime.

We believe that 12 hours is the shortest time-on-station of interest in the present study. The longer minimum time-on-station, 324 hours, has its basis in suggestions by the aerospace medical community that 14 days (336 hours) is about the longest a crew could be expected to tolerate an airplane's inherent noise and vibration levels [10]. Thus, the two times-on-station illustrated in Fig. 24 represent the likely extremes that might be required by any of the station-keeping missions and are consistently used for this purpose throughout our analysis.

Consider next the VLA-NUC for the longer time-on-station. For this, all 112 UE aircraft are able to serve as carriers and, therefore,

on-station performance decreases only slightly as the station radius increases. The slight decrease occurs, of course, because some of the available operational time is lost flying to and from the station and because we have assumed a constant OR rate. This effect is more significant for the nuclear airplane in the 12-hour minimum time-on-station. Clearly, as the station radius gets larger, the airplane spends a larger and larger fraction of its available operational time flying to and from the station-keeping point.

Similar characteristics can also be observed for the VLA-JP. In this instance, performance is markedly degraded (when compared with the nuclear airplane) since some fraction of the 112 UE aircraft must serve as tankers to support the station-keeping airplanes (i.e., the carriers). Note, however, that even for VLA-JPs, somewhat better station-keeping performance is obtained for the longer time-on-station. Again, this is attributed to the carrier aircraft's spending relatively less operational time getting to and from the station-keeping point.

We remind the reader that the payload maintained on-station continuously should only be regarded as a proximate measure of effectiveness for the station-keeping missions. However, since we are examining these missions in a generic sense and since our primary objective is to identify the most attractive airplane alternatives for this wide class of missions, the measure seems appropriate.

From Fig. 24, it is obvious that, for the same number of UE station-keepers, the nuclear airplanes will provide much greater capability than the chemical-fueled airplanes at any station radius. Indeed, such a result should not be unexpected since the endurance characteristics of nuclear-powered airplanes are perhaps their most attractive feature. Again, however, comparing alternatives will be greatly facilitated by developing cost-effectiveness and energy-effectiveness metrics; how this is accomplished is shown below by an example.

Sample Detailed Results

Table 22 presents details for the station-keeping mission that are analogous to those presented earlier for the strategic airlift missions. Specifically, Table 22 depicts analysis results for a station radius of 1500 n mi and a 12-hour minimum time-on-station for each of the seven

Table 22

DETAILS OF THE STATION-KEEPING ANALYSIS FOR A
1500 N MI STATION RADIUS AND A 12-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	134	93	93	95	112	85	194
Carrier UTE rate	12.7	12.9	12.9	13.0	12.8	12.9	12.8
UE tankers	91	19	19	17	0	11	0
Tanker UTE rate	11.2	11.2	11.2	11.2	0	11.2	0
Average OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	12.1	12.6	12.6	12.7	12.8	12.7	12.8
Costs (billions 1975 $)							
Acquisition	4.77	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous airborne alert)	64.26	60.13	73.39	97.15	80.91	102.37	99.84
Energy (Quads)							
Aircraft manufacture	0.09	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous airborne alert)	14.87	12.00	14.54	17.28	30.59	18.13	38.55
Capability							
Time-on-station (hrs)	14	17	17	21	16	19	16
Avg UE on-station	47	35	35	38	41	33	71
Payload-on-station (tons)	4660	6120	6150	6740	7210	7310	8204
Cost-Effectiveness ($ bil/kiloton)	14.82	10.88	13.04	15.23	13.61	14.83	14.74
Energy-Effectiveness (Quads/kiloton)	3.21	1.98	2.39	2.58	4.30	2.50	4.76

alternative airplanes. These results are presented in terms of operational characteristics, life-cycle costs, life-cycle energy consumption, and resulting capability.

Note that in a maximum continuous airborne alert, a very high average UTE rate would have to be maintained--ranging from a low of about 12.1 hours for the C-5B to about 12.8 hours for the nuclear airplanes. A direct result of the high UTE rates are the very substantial 20-year operating and support costs. Over 20 years, the station-keeping aircraft would accumulate on the order of 100,000 flying hours per aircraft. Indeed, the primary reason for having procured the same number of airplanes as the number required for the airlift mission is the presumption that, at some stage of their life cycle, the station-keeping and the airlift fleets could be interchanged, as discussed previously. Note also how the total energy requirement for 20 years' fuel dominates any energy that might have been expended in aircraft acquisition.[a]

The first parameter shown under capability is the actual time-on-station. For the 12-hour minimum time-on-station, the chemical-fueled airplanes range from a low of 14 hours to a high of 21 hours. To make our examination of the nuclear airplane comparable, we have specified its time-on-station as 16 hours. We also show the average number of UE on-station at any given moment and the average payload on-station. Using this latter measure of effectiveness, the nuclear airplanes show the greatest capability; the C-5Bs the least.

Cost-effectiveness and energy-effectiveness parameters are the final two entries in Table 22. Both cost and energy are quantified by their life-cycle values, in billions of 1975 dollars and Quads of energy, respectively; the average payload maintained on-station in thousands of tons serves as the proxy for effectiveness. For the 12-hour minimum time-on-station, the VLA-JP has the most attractive cost-effectiveness and energy-effectiveness parameters (i.e., least cost or energy per ton of payload on-station). The least cost-effective are the hydrogen airplanes and the least energy-effective the nuclear

[a]Of course, a reduced airborne alert would yield substantially lower O&S costs. We have examined such cases and describe the results later in this section.

airplanes. Clearly, these results will change somewhat if we extend the time-on-station at the same station radius as illustrated next.

Table 23 presents information similar to that shown in Table 22, except that the minimum time-on-station has been increased from 12 hours to 324 hours. The principal changes are in the average UE on-station and the payload on-station. Observe also that the generally higher average UTE rates for this mission profile cause corresponding changes in the 20-year O&S costs and energy consumption.

In terms of cost-effectiveness, the VLA-NUC now looks most attractive, but it has only a slight advantage over the VLA-JP. In energy-effectiveness, the nuclear airplanes still appear least attractive and the VLA-JP the most.

We repeated this type of analysis for all five of the previously described station radii, using these two extremes of station-keeping duration. Tables 24 and 25 summarize the results for these station-keeping missions, in a form similar to that for the results of the strategic airlift missions. (See Appendix G for more detail on the station-keeping mission analyses.)

SUMMARY COMPARISON

We first make a summary comparison of all seven alternative airplanes. Logically stemming from this comparison is a more detailed examination of the relative merits of the VLA-JP and the VLA-NUC alternatives, the two alternatives that emerge as having the most potential.

Comparison of All Alternatives

Table 24 summarizes the relative cost-effectiveness and energy-effectiveness of the seven alternative airplanes for each of the selected station radii, assuming a 12-hour minimum time-on-station. Again, we have normalized each entry by using the C-5B and its zero station radius-mission profile as the base. And, once again, the least attractive alternatives, the most attractive, and those in the intermediate range are highlighted.

Table 23

DETAILS OF THE STATION-KEEPING ANALYSIS FOR A
1500 N MI STATION RADIUS AND A 324-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	107	71	71	81	112	73	194
Carrier UTE rate	13.8	13.8	13.8	13.8	13.8	13.8	13.8
UE tankers	118	41	41	31	0	23	0
Tanker UTE rate	11.2	11.2	11.2	11.2	0	11.2	0
Average OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	12.4	12.8	12.8	13.1	13.8	13.2	13.8
Costs (billions 1975 $)							
Acquisition	4.77	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous airborne alert)	65.79	61.17	74.69	99.86	86.40	105.98	106.51
Energy (Quads)							
Aircraft manufacture	0.09	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous airborne alert)	15.28	12.23	14.82	17.80	32.98	18.81	41.56
Capability							
Time-on-station (hrs)	325	325	331	335	336	329	336
Avg UE on-station	60	40	40	46	63	41	110
Payload-on-station (tons)	6040	7010	7010	8000	11,060	8110	12,590
Cost-Effectiveness ($ bil/kiloton)	11.68	9.64	11.62	13.17	9.36	13.81	10.13
Energy-Effectiveness (Quads/kiloton)	2.55	1.76	2.13	2.24	3.02	2.33	3.34

Table 24

SUMMARY OF COST AND ENERGY EFFECTIVENESS FOR STATION-KEEPING MISSIONS (CONTINUOUS AIRBORNE ALERT—12-HOUR MINIMUM TIME-ON-STATION)

Station radius (n mi)	C-5B	VLA-JP	VLA-LCH$_4$	VLA-LH$_2$	VLA-NUC	VLA-LH$_2^*$	VLA-NUC*
Relative cost							
0	1.00	1.01	1.21	1.54	1.47	1.51	1.59
1500	2.24	1.65	1.98	2.31	2.06	2.25	2.23
3000	5.00	2.90	3.96	3.66	2.66	3.54	2.88
4500	8.85	5.15	5.82	6.45	3.25	6.41	3.76
6000	(a)	8.45	10.00	8.49	3.84	9.23	4.15
Relative energy							
0	1.00	0.85	1.03	1.21	2.14	1.17	2.37
1500	2.24	1.40	1.68	1.82	3.03	1.76	3.35
3000	5.00	2.46	3.37	2.89	3.93	2.78	4.35
4500	8.85	4.37	5.41	5.09	4.80	5.02	5.69
6000	(a)	7.17	8.53	6.71	5.69	7.24	6.30

Most attractive Intermediate Least attractive

[a] Unable to fly this mission

A careful examination indicates that the VLA-JP has the most attractive cost-effectiveness and energy-effectiveness characteristics for the shorter station radii. For the longer radii, the VLA-NUC is clearly most attractive, at least, in terms of cost-effectiveness. None of the cryogenic-fueled airplanes appears to offer any advantage in either cost-effectiveness or energy-effectiveness over the VLA-JP or VLA-NUC. Except at zero station radius, the C-5B is inferior to the VLA alternatives; indeed, it is actually incapable of performing the 6000 n mi station radius mission (see Appendix G).

Similar results for a 324-hour minimum time-on-station are displayed in Table 25. These show a trend similar to that observed for the 12-hour minimum time-on-station, except that the longest station radius for which the VLA-JP airplane looks more attractive

Table 25

SUMMARY OF COST AND ENERGY EFFECTIVENESS FOR STATION-KEEPING MISSIONS (CONTINUOUS AIRBORNE ALERT—324-HOUR MINIMUM TIME-ON-STATION)

Station radius (n mi)	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2^*	VLA-NUC*
Relative cost							
0	1.00	1.03	1.25	1.55	1.39	1.51	1.50
1500	1.77	1.46	1.76	2.00	1.42	2.09	1.53
3000	3.56	2.36	2.85	2.71	1.45	2.41	1.56
4500	6.21	3.61	4.36	3.80	1.47	3.59	1.59
6000	(a)	5.51	6.34	5.62	1.50	4.54	1.63
Relative energy							
0	1.00	0.87	1.05	1.22	2.06	1.17	2.28
1500	1.77	1.23	1.48	1.56	2.10	1.62	2.32
3000	3.56	1.98	2.40	2.12	2.14	1.87	2.37
4500	6.21	3.01	3.68	2.97	2.18	2.79	2.42
6000	(a)	4.64	5.35	4.39	2.22	3.53	2.46

Most attractive Intermediate Least attractive

[a] Unable to fly this mission

than the nuclear is substantially lessened. Again, there is no apparent reason for pursuing any of the alternatives except the VLA-JP and VLA-NUC.

More detailed comparisons of the JP- and nuclear-fueled airplanes therefore seem appropriate. Our objective is to define more closely the break-even point between the two alternatives. In other words, at what station radius does the nuclear airplane begin to look substantially more attractive than the VLA-JP alternative? This comparison will be performed in terms of cost-effectiveness only. Note in Tables 24 and 25 that the nuclear airplanes are more energy effective than the VLA-JP for only the very longest station radii.

Detailed Comparison of the VLA-JP and the VLA-NUC

The cost-effectiveness of the VLA-JP and the VLA-NUC airplanes is displayed in Fig. 25 for a 12-hour minimum time-on-station.

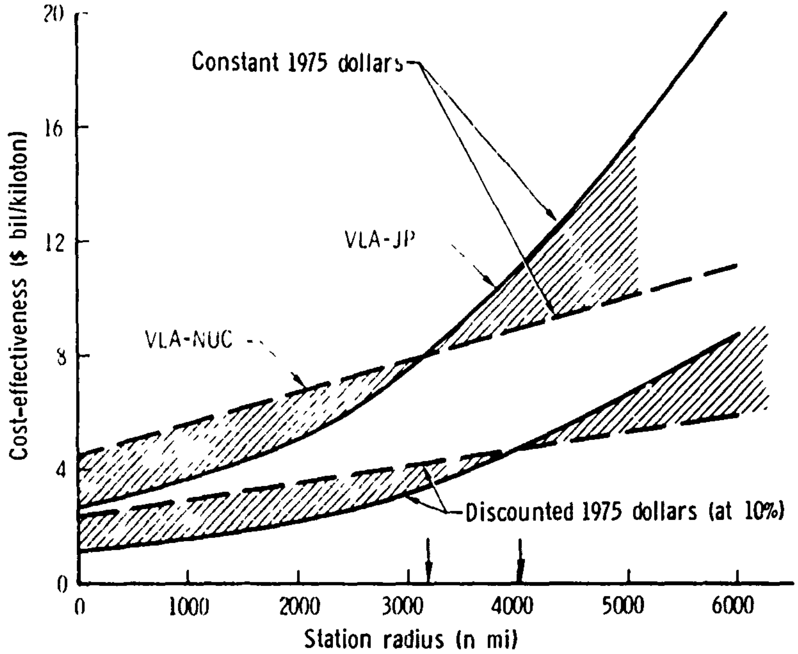

Fig. 25 — Cost-effectiveness of JP- and nuclear-fueled airplanes in station-keeping applications, for 12-hr minimum time-on-station (life-cycle costs based based on 90 flying hours/month/aircraft)

These extended comparisons assume the peacetime level of flying activity has been reduced to about 90 hours per month per aircraft. This would provide about 20 percent of the capability that would obtain for a maximum continuous airborne alert. The life-cycle costs used in the calculation of cost-effectiveness have been determined using this reduced UTE rate. Our measure of effectiveness, however, is still that obtained for a maximum airborne alert (i.e., for the wartime capability). Thus, the approach is quite similar to that used to describe costs and effectiveness for the strategic airlift mission.[a]

Consider first the comparison between the VLA-JP and the VLA-NUC in which the cost-effectiveness is based on constant 1975 dollars.

[a]We believe the reduced airborne alert in peacetime is more representative of how the station-keepers might actually be operated. However, had the life-cycle costs been based on higher UTE rates (as in the maximum continuous airborne alert case), the analytical results presented in the following paragraphs would be qualitatively unchanged.

Figure 25 indicates that the crossover point occurs at approximately 3200 n mi. Thus, for smaller station radii the VLA-JP is more cost-effective; for station radii in excess of 3200 n mi, the nuclear airplane is.

Because the nuclear airplane involves much larger acquisition costs but promises somewhat lower fuel costs,[a] using discounted 1975 dollars to determine cost-effectiveness also seemed advisable. For a 10 percent discount rate, the crossover point occurs at about 4000 n mi. Remember that the station-keeping airplanes' acquisition costs have, in this analysis, been calculated for a second-production buy. Thus, the substantially greater RDT&E costs for nuclear airplanes are not included in the discounting scheme. Including them could make the nuclear airplane relatively less cost-effective.

Finally, one additional aspect of this comparison is of significance. The crossover point is only of real interest if one assumes that the entire fleet of station-keeping airplanes is flying missions that have the same radius. However, quite probably the airplanes would be employed in a variety of roles--at several different station radii. To take the other extreme, one might also assume that the on-station airplanes are distributed uniformly from a zero station radius out to some maximum station radius.[b] Under these circumstances the break-even point can again be located; it occurs when the shaded area to the left of the intersection of the curves (at 3200 or 4000 n mi) is equal to the shaded area to the right (the right-hand boundary of the shaded area delineates the break-even radius).

For constant 1975 dollars, the break-even point determined in this fashion is about 5100 n mi. Stated another way, if the airplanes are uniformly distributed, the maximum station radius must be greater than 5100 n mi for the nuclear airplane to be the most attractive.

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[a]Of course, when flying a station-keeping mission profile, the nuclear airplanes consume relatively less JP than what is shown in Appendix D. The O&S cost estimates for the VLA-NUC reflect this lessened use of JP, which is more expensive per unit of energy.

[b]An equivalent interpretation is to assume that there is an equal likelihood of deploying all the station-keepers to any station radius between zero and the maximum.

The same argument holds true for discounted 1975 dollars. In this case, the maximum station radius for a uniform distribution would be in excess of 6000 n mi. In other words, for all of the missions that can be considered viable by our earlier arguments, the VLA-JP would always be more cost-effective than the VLA-NUC if the carrier aircraft are uniformly distributed over the range of station radii of interest.

Our previous results indicated that the nuclear airplane demonstrated substantially greater capability for the 324-hour mission time-on-station. Thus, one would most certainly want to employ that airplane in a profile with a long time-on-station whenever possible. However, we should mention that certain applications, like the tactical battle platform mission, might involve, at least in wartime, expending consumables at a fairly high rate (such consumables as fuel for RPVs or manned fighters, weapons for those vehicles, etc.). Consequently, for applications of this sort, the 12-hour minimum time-on-station may be the realistic maximum station duration, with the carrier airplane then returning to its home base for replenishment.

In Fig. 26, the previous results are replicated except for a 324-hour minimum time-on-station rather than a 12-hour one. The crossover points defined by the intersection of the curves occur at about 1800 n mi for the constant 1975 dollars situation and 2500 n mi for the discounted dollars. If a uniform distribution of station radii is assumed for the station-keepers, the maximum station radius, in the case of constant 1975 dollars, must be at least 3200 n mi for the VLA-NUC to look most attractive. If discounted 1975 dollars are used, this maximum station radius extends to about 4500 n mi.

Not surprisingly, the VLA-NUC appears substantially more attractive for the longer time-on-station case--regardless of which view (constant dollars, discounted dollars, or operational concept) is adopted.

In what follows, we attempt to synthesize the observations made in conjunction with Figs. 25 and 26. Figure 27 summarizes the preceding cost-effectiveness comparisons just made of the VLA-JP and VLA-NUC. Our objective here is to delineate the regions of the mission parameter space (i.e., the space defined by the time-on-station and station radius limits considered in the analysis) in which each of the alternatives is the most

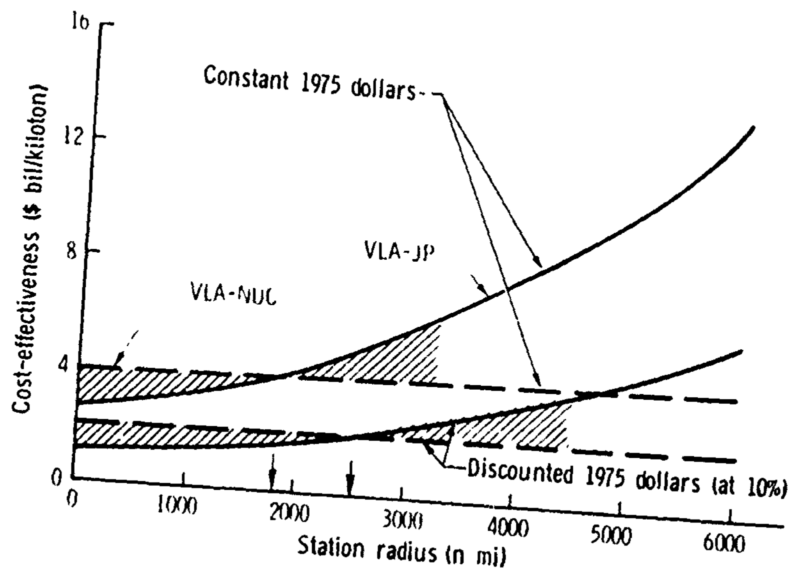

Fig. 26—Cost-effectiveness of JP- and nuclear-fueled airplanes in station-keeping applications, for 324-hour minimum time-on-station (life-cycle costs on 90 flying hours/month/aircraft)

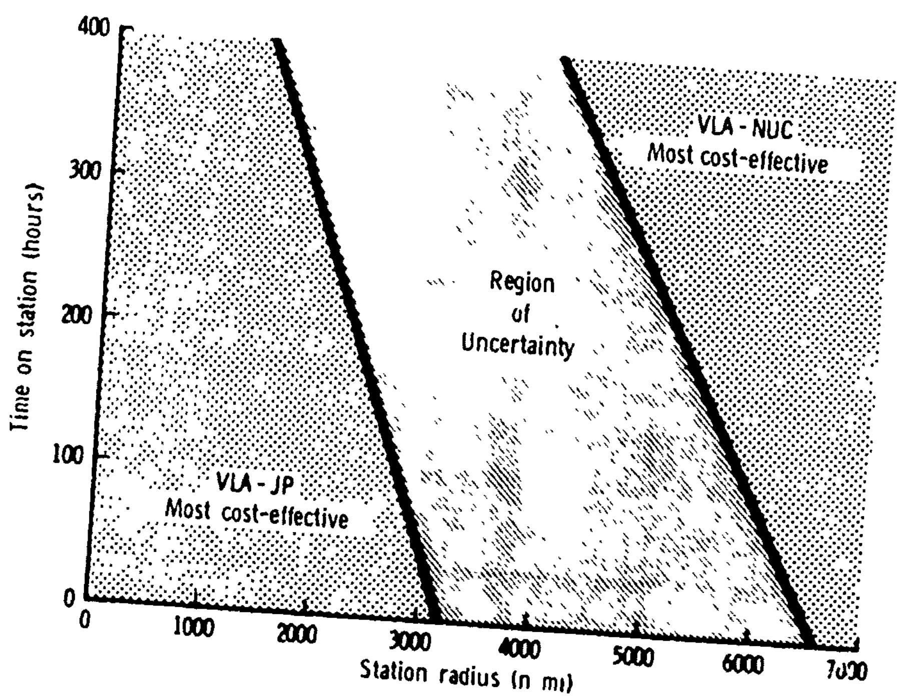

Fig. 27—Summary of the relative cost-effectiveness of the VLA-JP vs. VLA-NUC for station-keeping missions

cost-effective. The boundary on the left side of the figure (which divides the region in which the VLA-JP is shown as most cost-effective from the so-called region of uncertainty) has been determined from the intersection points of the cost-effectiveness curves (for constant 1975 dollars) shown in Figs. 25 and 26. Similarly, the boundary on the right is based on the required maximum station radius for a uniform distribution of station-keepers (using discounted 1975 dollars) taken from the same two figures. Thus, the region of uncertainty reflects the mission parameter space in which either alternative can be argued as cost-effective--depending on one's perspective.

From Fig. 27, it is clear that the VLA-JP is most cost-effective for station radii of less than about 2000 n mi, regardless of the time-on-station. At station radii greater than 4000 n mi, the VLA-NUC begins to dominate as the most cost-effective.

Consider the region for which the VLA-NUC is without doubt the most cost-effective. From Fig. 22, it was clear that very few viable missions, except the tactical battle platform one, had station radii greater than 4000 n mi. Furthermore, as noted previously, tactical battle platform missions in wartime would probably involve relatively short periods on-station (perhaps less than 24 hours). These facts suggest that the mission parameters for which the VLA-NUC is dominantly cost-effective may be of little interest--at least for the station-keeping missions that we have discussed. Of course, if the region of uncertainty is apportioned between the JP and nuclear alternatives, different conclusions can be drawn. However, our principal observation is that the VLA-NUC dominates in cost-effectiveness for only a relatively small (and perhaps uninteresting) region of the mission parameter space.

These results for the station-keeping missions must be considered in concert with the results for the strategic airlift mission. The life-cycle costs of the station-keepers, for example, have been determined by assuming that airplanes of the same type have previously been procured for use as airlifters. If JP-fueled airplanes were procured as airlifters (because of their relatively more attractive cost-effectiveness and energy-effectiveness) but nuclear airplanes were desired for the station-keeping role, the results shown in Figs. 25

through 27 would change markedly. Specifically, charging the RDT&E costs and the resulting greater unit flyaway costs against the VLA-NUC station-keepers would make the nuclear alternative substantially less cost-effective than they are in Figs. 25 to 27. On the other hand, if nuclear airplanes were desired exclusively for the station-keeping role, it might be possible to relax the design constraints and thus mitigate some of these increases in cost.[a]

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[a]For example, if the nuclear airplanes were configured as seaplanes, as mentioned in Section IV, their cost-effectiveness in the station-keeping role might be significantly enhanced.

IX. CONCLUSIONS

The two principal objectives of the research described in this report have been to determine the most attractive aircraft fuel for future Air Force use and to provide some insights regarding the military utility of airplanes that have a gross weight of from one to two million pounds. This section presents our summary observations and conclusions.

Clearly, the validity of these observations is highly dependent on the uncertainties inherent in any analysis of this type. We therefore discuss how such uncertainties might affect our results. We then analyze the implications of foreseeable advances in technology, and conclude with an explanation of why we feel our results can be regarded with a relatively high degree of confidence.

SUMMARY OBSERVATIONS

The liquid-methane-, liquid-hydrogen-, and nuclear-fueled very large airplanes appear to be the least attractive alternatives for the strategic airlift mission and the JP-fueled VLA the most attractive. However, our results indicate that, in terms of cost-effectiveness, the C-5B is a potentially attractive competitor of the VLA-JP--at least for certain of the deployment missions analyzed.

For the station-keeping missions, the C-5B, the liquid-methane, and the liquid-hydrogen VLAs proved to be the least attractive. The VLA-JP appeared the most attractive station-keeper for the smaller station radii, whereas the nuclear-powered VLA was most attractive for larger station radii. Our results indicated that the station-radius crossover point was in excess of 4000 n mi; that is, for station radii greater than 4000 n mi, the VLA-NUC begins to be dominantly more attractive than the VLA-JP.

Most Attractive Aircraft Fuel

A liquid hydrocarbon jet fuel, similar to today's JP-4 or JP-8, is clearly the most cost-effective and energy-effective fuel for very

large airplanes. Such a fuel could be synthesized from coal, oil shale, or (presuming that other energy consuming sectors reduce their demand for petroleum products) refined from crude oil as it is today.

This conclusion is substantially strengthened by two additional observations. First, a JP-type fuel is almost certainly preferable for the other types of aircraft within the Air Force inventory--like fighters. We know of no studies which suggest that any other fuel alternative is suitable for these smaller airplanes. Secondly, continued use of a conventional jet fuel should ease the problems associated with making the transition from crude oil to other primary energy resources. Indeed, a recent change in Defense Department policy requires that

> All new turbine powered aircraft shall be designed to operate on middle distillate turbine fuel, JP-8, as well as on JP-5 and JP-4 [54].

Such flexibility is important because the desirable specifications for synthetic jet fuels are still uncertain (see Section X).

Liquid hydrogen and liquid methane pose difficult development problems and may result in aircraft fleets that are operationally constrained because of the limited availability of these fuels outside of CONUS. Our study indicates that neither cryogenic fuel results in a significant savings of cost or energy. Thus, we see no incentive to develop military aircraft which would use these fuels--at least, until U.S. petroleum, oil shale, and coal resources are near exhaustion. Associated analyses suggest that our coal resources will be less than 50 percent depleted by 2025 [19]. Thus, utilization of cryogenic fuels in aircraft entering the Air Force inventory before the end of the century need not be considered (use of liquid methane under these circumstances would, of course, require an appropriate source of carbon).

Although our analysis indicated little potential for aircraft nuclear propulsion, modification of the design constraints imposed upon the VLA-NUC (and VLA-NUC*) could enhance its attractiveness. For example, shutdown of the reactor during takeoff and landing may not significantly improve the safety characteristics of nuclear airplanes.

If that is so, employing full reactor power during takeoff (probably with some assistance from chemical fuel) would result in substantial reductions in aircraft gross weight. On the other hand, more stringent crash containment criteria may be needed, and these would result in a still heavier reactor system. In general, much uncertainty exists in the weight estimates of the nuclear reactor system.

The Potential of Very Large Airplanes

Our results indicate that very large airplanes may not be substantially more cost-effective than contemporary airplanes for certain airlift mission applications. Indeed, for some mission scenarios (e.g., NATO reinforcement--assuming fuel is available for the return leg), the C-5B displayed a somewhat better cost-effectiveness.

On the other hand, the very large airplanes clearly enhance the capability to perform missions not routinely performed at present. They could provide an essentially worldwide airlift deployment capability that does not rely on overseas bases--at least, on overseas bases not owned by the United States. For the station-keeping missions, the VLAs provide much greater flexibility than existing equipment. In all these applications, the VLA-JP will be both more cost-effective and energy-effective than any contemporary airplane. (The superiority of the VLA-JP is, of course, partially attributable to its incorporating some modestly advanced technology the C-5B does not have; the attractiveness of the VLA-JP is, therefore, not wholly a consequence of its size.)

As we will shortly explain, certain biases against the VLA-JP have been (by intent) built into our analysis. Without these, the VLA-JP would, in all likelihood, dominate the C-5B (or other contemporary equipment) in all measures of merit even more strongly.

Thus, the overall attractiveness of the VLA-JP should be apparent. We are not suggesting, however, that a firm requirement exists for an aircraft sized to the design constraints developed in this research. Rather, the VLA-JP was intended simply to represent an airplane substantially larger than any now available. That the VLA-JP appears attractive in a variety of mission applications does indicate that a

class of airplanes (in which the VLA-JP is probably the upper limit in terms of size) should be subject to more detailed analyses; with these analyses it should be possible to identify the ultimately required design constraints. (See the recommendations presented in the next section.)

These conclusions are principally based on the previously presented cost-effectiveness and energy-effectiveness of each alternative in the various mission applications. When considering the merit of alternative weapon systems, many other issues (e.g., vulnerability) should be taken into account. If a perfect systems analysis were possible, such issues could be explicitly included in the cost, energy, and effectiveness metrics. Since analytical perfection is seldom, if ever, attained (and certainly not in the present work), we have resorted to a qualitative discussion of the relative merits of each alternative with respect to a host of these auxiliary issues. This discussion is presented in Appendix H; the issues identified are technical risk, basing flexibility, routing flexibility, in-flight vulnerability, prelaunch survivability, development potential, crew safety, public safety,[a] air and noise pollution, energy and water resource depletion, land-use impact, and perceived threat value. Our analysis suggests that none of the aircraft alternatives would be more attractive than the VLA-JP when these issues are included in the deliberation.

THE EFFECTS OF UNCERTAINTIES

Many factors enter into any broad-brush systems analysis and each such factor has some uncertainty associated with it. In the following paragraphs, we will address some of these and then infer their implications for previously presented observations. Here, of course,

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[a]The safety aspects of nuclear-powered airplanes are sufficiently important to be more extensively addressed in Appendix I.

we are primarily concerned with those aspects of the analysis that might affect the *relative* attractiveness of the alternatives.[a]

Implications of Advanced Technology

Aircraft Technology (Conventional Aircraft). As noted previously, the conceptual designs of the alternative very large airplanes explicitly incorporate little advanced technology (except for the modest assumptions regarding the turbofan engines). How the inclusion of such advances might affect our analysis is of obvious importance.

Figure 28 highlights the differences in four distinct conceptual designs of the VLA-JP.[b] The first design in Fig. 28 (denoted ASD) is the one used in our analysis; it is described in Appendixes A and B. Three of the conceptual designs are based on the existing technology (i.e., represent aircraft which could be operational by 1985). The fourth design incorporates substantial advances in the technology, such as composite material in primary structure and advanced engines. Such an airplane might become operational in the 1990s.

Two important deductions can be made from Fig. 28:

- The conceptual design employed in our analysis (ASD) is the most conservative of the three that represent current technology. (That is, the ASD design implies that an airplane with greater empty weight and gross weight is required to perform the design mission.)

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[a]Numerous assumptions implicit to our analysis could markedly alter the results in an absolute sense, but have little, if any, bearing from a relative viewpoint. Consider, for example, the strategic airlift mission analysis. Our approach did not include such operational problems as in-flight mission aborts, adverse weather, etc., but it is difficult to imagine that incorporating such refinements would change the outcome of the analysis. Note, however, that such refinements would be necessary if the results were to be compared with other means of accomplishing the mission--such as sealift.

[b]The authors are grateful to Mr. Roy Lange of the Lockheed-Georgia Company and Mr. Dan Brewer of the Lockheed-California Company, who provided the design results indicated in Fig. 28.

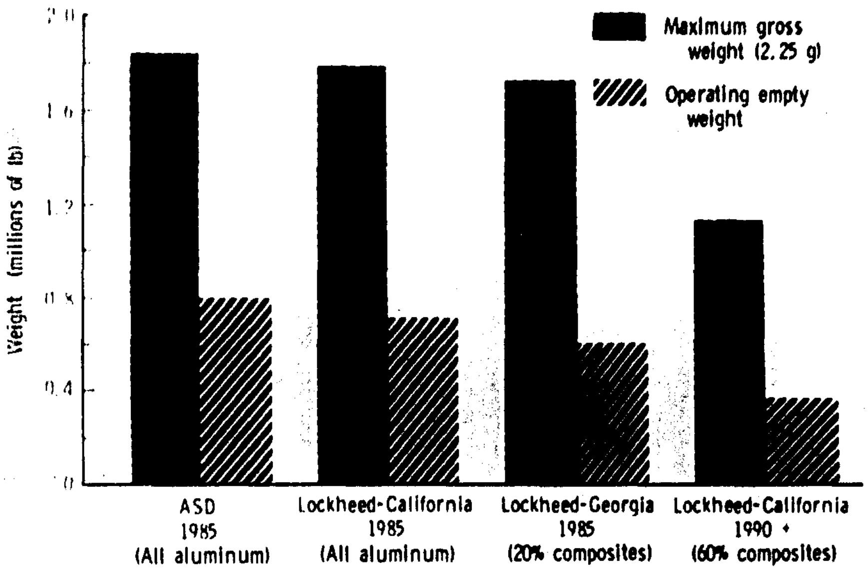

Fig. 28—Comparison of the empty and maximum gross weights of several VLA-JP conceptual designs, with the year in which it is assumed to become operational shown for each airplane (NOTE: Lockheed estimates are based on preliminary conceptual designs of transport aircraft)

- Advanced technology holds the promise of significantly enhancing the attractiveness of the VLA-JP alternative.[a]

Thus, we feel confident that our comparisons between the VLA-JP and the C-5B are strongly biased in favor of the contemporary airplane. In other words, a more detailed design analysis--particularly if advanced technology is included--would tend to portray the VLA-JP as even more desirable (compared to a contemporary airplane) than that inferred from our previous presentations.

The next obvious question is: How will advanced aircraft technology affect the relative merit of the other VLAs? Since the preceding argument confirmed the superiority of the VLA-JP over contemporary large airplanes, we need only be concerned with how the other VLAs compare to the VLA-JP for similar advances in the technology.

[a]Of course, advanced technology would also enhance the attractiveness of new airplanes smaller than the VLA-JP.

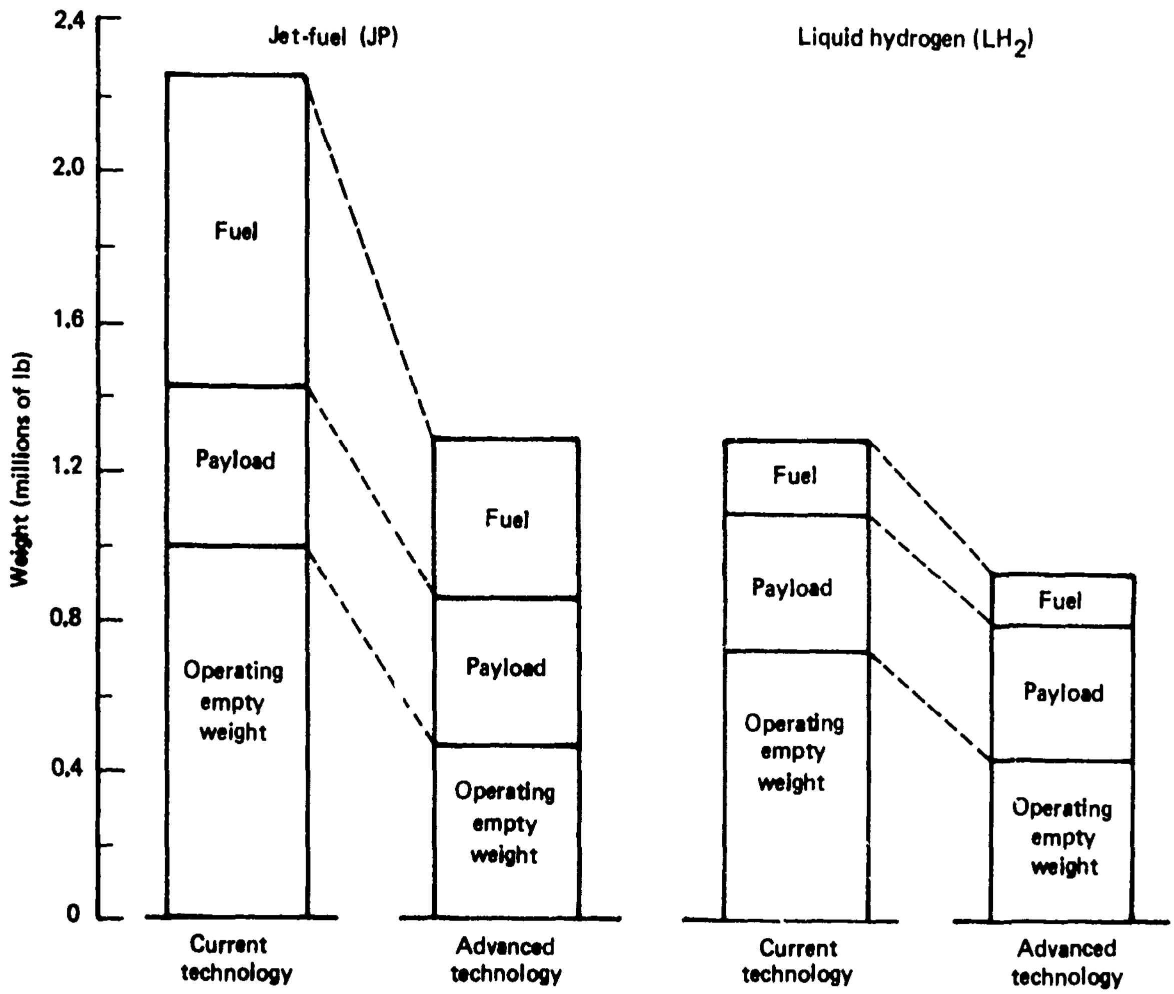

Fig. 29—The effect of advanced technology on the weights of JP- and LH_2-fueled aircraft source (Source: Preliminary conceptual design estimates by Lockheed-California Co. for transport aircraft)

Insights into the above question are provided by Fig. 29 which compares the effect of advanced technology on airplanes fueled with JP or LH_2. (In Fig. 29, the definitions of current and advanced technology are identical to those presented in conjunction with Fig. 28.[a])

[a]Indeed, all airplanes in Fig. 29 are sized to the same design point as the VLA-JP, except that a limit load factor of 2.50 g has been assumed rather than the 2.25 g used in most other places in this report. This difference in load factor is thought to be inconsequential to the comparison being made.

Note that incorporating 1990 technology has very positive effects for both JP and LH_2, but that, as Table 26 shows, the percentage improvement is more significant for the JP-fueled airplane.

Thus, the implication of Fig. 29 and Table 26 is that advanced technology would benefit the VLA-JP more significantly than the VLA-LH_2. Why this would be so can be explained as follows. The effect of any advance in aircraft technology is to reduce the energy requirements of the flight vehicle. For example, employing composite

Table 26

REPRESENTATIVE PERCENTAGE IMPROVEMENTS FROM INCORPORATING ADVANCED TECHNOLOGY

	JP-Fueled Aircraft	LH_2-Fueled Aircraft
Operating Empty Weight	53	40
Block Fuel Weight	48	34
Gross Weight	43	28

SOURCE: Figure 29.

material reduces the weight of the airframe, thus reducing the propulsive power required, assuming the aerodynamic characteristics remain unchanged. Similarly, aerodynamic improvements accomplish the same goal by increasing the lift-to-drag ratio. When advanced technology is applied to some baseline design sized for a specific mission, the improved design for accomplishing the same mission must be resized to account for the resulting reduction in the energy required to perform the mission. This resizing would provide more pronounced improvements for JP-fueled aircraft relative to LH_2, since JP is much heavier per unit energy. That is, a reduction in the fuel-energy required by the application of advanced technology provides a greater absolute reduction in fuel-weight for JP compared to LH_2; this reduced fuel-weight is magnified when the airplane is resized to perform the original design mission, because reducing JP weight provides a greater percentage reduction in gross weight.

The above reasoning suggests that the application of advanced technology to liquid-methane-fueled airplanes would result in only slightly less improvement than that displayed by JP-fueled aircraft. Nonetheless, neither cryogenic-fueled alternative displays greater promise from the application of advanced aircraft technology than the VLA-JP.[a]

Much the same fate awaits the nuclear-powered airplanes when they are similarly examined. For these, advances in aircraft state of the art imply a reduction in the reactor power required. To illustrate the likely effect, the VLA-NUC employs a 535-MW reactor and the VLA-NUC*, a 390-MW one. Yet this 27 percent reduction in reactor power reduces the weight of the reactor and containment vessel system only 15 percent. Of course, this occurs primarily because the weight of the containment vessel is not strongly dependent on design power-level. Once again, then, the advantages of advanced aircraft technology are more favorable for JP-fueled airplanes.

Fusion Reactors. In the introduction to this report, we observed that controlled thermonuclear reactors offer great promise as an eventual source of essentially unlimited energy. Whether such reactors could be employed for aircraft propulsion is a question of obvious importance.

Although examining the potential applications of this largely undeveloped technology is, to say the least, risky, such an analysis has recently been informally performed at Rand.[b] It concluded that a laser fusion reactor system would probably be about twice as heavy as a fission system for the same power output. The greater weight is largely a consequence of the shielding required to contain the high energy neutrons and gamma rays. Such shielding is available with existing technology (and its weight is not likely to be reduced by advanced technology); furthermore, all fusion reactors would require similar shielding--regardless of their eventual evolution.

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[a]The likely effect of advances in the fuel supply processes for the cryogenic alternatives is deferred to the last subsection.

[b]These calculations were performed by Dr. Harry Watanabe.

Therefore, fusion does not appear to offer great promise for direct aircraft propulsion. Were the technology available, however, it would obviously lessen the demand for liquid hydrocarbon fuels by other consuming sectors and, thus, greatly alleviate any future shortages of aviation fuels.

Unconventional Aircraft. This final class of advanced technology has not yet been discussed. Although many configurations have been proposed in the last several years, the most promising has been some type of spanloader or distributed load airplane (i.e., essentially a flying wing) [64]. These are of interest because they offer the possibility of eliminating entirely the drag contribution of the fuselage.

Such concepts have recently been evaluated in detail by the major airframe manufacturers [65,66,67]. The overall conclusion of these analyses is that the spanloader does not appear to offer the advantages originally anticipated.

We should note that such unconventional designs are not likely to affect the relative attractiveness of the fuel alternatives. Indeed, most of the earlier discussion should be applicable to this class of advanced technology also. (Nuclear power may be particularly inappropriate for distributed load airplanes since the reactor system represents an unwanted concentrated mass.)

Interest has been recently revived in lighter-than-air vehicles. To date, research on purely buoyant vehicles and also on hybrid concepts (i.e., generating aerodynamic lift in addition to buoyant lift) has generally suggested that they would be inferior to airplanes in most applications--particularly in those where speed (i.e., productivity) is significant.

We are unaware of any other unconventional design concepts (excluding those such as multilobe fuselages, which are actually variations applied to conventional airplanes) that offer the potential for significant quantum improvements in airplane performance.

Overall Confidence in the Present Analysis

What degree of confidence can be placed in this analysis? The careful reader may recall that, by design, many of the uncertainties

that came up were resolved in favor of alternatives other than the VLA-JP. For example, in Appendix F our approach for estimating average payloads in the strategic airlift missions may have undervalued the capability of the VLA-JP compared to the nuclear airplanes, the liquid-hydrogen airplanes, or the C-5B. In the just-concluded evaluations of the effects of advanced technology the same bias has been demonstrated. That the VLA-JP still emerged as the most cost-effective and energy-effective alternative is, in our view, a powerful result.[a]

The following resolutions of uncertainty are also pertinent. For the C-5B, we assumed that all tanker operations are flown at a load factor of 2.00 g (ground-maneuver limit, see Appendix C). In the station-keeping missions, C-5B carriers receiving an aerial refueling were overloaded to an in-flight gross weight of 795,000 lb. Both assumptions substantially improve C-5B performance.

For the cryogenic airplanes, we assumed that the in-flight transfer of cryogenic fuel will present no unusual problems. A more important consideration for these alternatives, however, is the disparity between peacetime and wartime (or surge) utilization rates. Clearly, the fuel supply system must be sized for the wartime requirement. Stanley has observed that if the system operated at about 20 percent of its capacity in peacetime (and this would be the case if the peacetime UTE rate were 2 hours/day with a surge UTE rate of 10 hours/day), the unit fuel costs for LH_2 must be increased by a factor of almost three[b] in order to recover the costs of the liquefaction facility [19, 48]. The corresponding factor for liquid methane is somewhat less than 1.5. These calculations assume that interruptible peacetime uses of gaseous methane and hydrogen exist, but that no such interruptible market exists for the cryogenic liquids. This phenomenon does not occur for JP if peacetime users are assumed to be available. That is, we expect that refined syncrude products will be readily assimilated into a domestic peacetime market that now heavily relies on refined crude

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[a] This amounts to a classical *a fortiori* analysis [68].

[b] That is, three times the unit fuel cost used in our analysis, which presumed the system is operating at full capacity.

oil as a source of liquid fuels. No interruptible users of appreciable amounts of liquid hydrogen or liquid methane as end-use fuel forms are apparent, at least, in the foreseeable future [69]. Therefore, one could argue that the unit energy costs for LH_2 and LCH_4 used in this analysis should be increased by factors of 3.0 and 1.5, respectively.

For the nuclear airplanes, we have consistently assumed that they will be permitted to overfly both the United States and other land masses with their reactors in operation. Indeed, their operations were assumed to be not restricted in any way. We further assumed that the cargo-carrying capabilities of the nuclear airplanes would not be affected by the subdivision of the cargo compartment to accommodate the reactor system.

Finally, some comments regarding the unit cost of the chemical fuels are warranted. Many investigators have recently reported such cost estimates. Perhaps the most complete of these analyses has been that performed by Witcofski of NASA [70]. He reported the following unit energy costs in 1974 dollars: \$4.40/MMBtu for LH_2, \$2.80/MMBtu for LCH_4, and \$3.20/MMBtu for synthetic JP. These calculations are based on the same assumed input coal cost used by Stanley [19,48]. However, other of Witcofski's assumptions, such as the financing rules and the energy content per pound,[a] are significantly different and this makes direct comparison with the fuel costs presented in Section V difficult. Nonetheless, it is interesting to speculate on how the markedly different unit fuel costs could affect our analysis. Taken at face value, the VLA-LH_2 would be much more competitive with the VLA-JP, and would probably prove to be the superior choice in most of the mission applications examined. Note, however, that incorporating the aforementioned disparity between peacetime and wartime utilization rates would result in a cost picture similar to that presented in our

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[a]Witcofski's costs are based on the higher heating values of the fuels; Stanley's on the lower heating value. (Although the former is common practice in the gas industry, the latter is more widely accepted.) Of course, when related to the fuel consumption of a given engine, the difference between higher and lower heating values must be explicitly taken into account.

analysis. Thus, even if our fuel cost estimates are significantly in error (in a relative sense),[a] there are compensating factors that lead us to be confident in the general conclusions of our analysis.[b] (Observe that the above logic may not apply to the use of liquid hydrogen by the commercial aviation sector.)

* * *

To summarize, conventional jet fuel (JP)--whether made from coal, oil shale, or crude oil--appears to be the most attractive aviation fuel for future Air Force use. This conclusion should be valid--at least for all airplanes entering the inventory before the year 2000 [19]. Furthermore, an advanced-technology, JP-fueled airplane with a maximum gross weight in excess of one million pounds should be more cost-effective and energy-effective in a wide variety of mission applications than any contemporary airplane.

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[a] We have much less confidence in our unit energy prices as absolutes. However, the principal goal of the synthetic fuels analysis was to generate cost and energy parameters that would be meaningful in relative comparisons [19].

[b] One of the primary reasons Witcofski's LH_2 costs are much smaller than ours is that he includes a new gaseous hydrogen production process. This "steam-iron" process, presently under development by the Institute of Gas Technology [71], promises to reduce the cost of gaseous hydrogen by as much as a factor of two. In our view, if such a process proves commercially viable, this cheap hydrogen can be more profitably exploited in ground-based applications. For example, hydrocracking is one of the most expensive steps in a synthetic crude oil refinery; using lower-cost hydrogen could substantially improve the economics of synthetic JP and other end-use fuels (e.g., gasoline) [19]. Stated another way, the costs (both in dollars and in energy) of hydrogen liquefaction suggest that LH_2 would be an attractive end-use fuel only in applications where its payoff is unquestionable (e.g., rocket propulsion); our study suggests that this does not appear to be the case for military aircraft.

X. RECOMMENDATIONS

The broad-ranging nature of this study makes two kinds of recommendations appropriate: (1) recommendations that relate to general Air Force policy on alternative fuels and very large airplanes and (2) recommended research and development activities. The second category of recommendations includes required system studies and needed hard R&D in specific technology areas. Since our study has emphasized breadth of scope, these latter recommendations identify particularly promising technology areas rather than detail specific programs.

ALTERNATIVE AIRCRAFT FUELS

No apparent reasons exist for the Air Force's actively pursuing R&D that is aimed at the utilization of cryogenic fuels in aircraft entering the inventory before the end of the century.[a] Neither liquid hydrogen nor liquid methane is likely to be more cost-effective or energy-effective in the large, subsonic airplane application than synthetic JP. This conclusion is further strengthened by the unsuitability of the cryogenic fuels for use in smaller airplanes like fighters. Furthermore, NASA's ongoing work on the potential utilization of LH_2 as a fuel for commercial aircraft is sufficient to keep the Air Force's options open should developments not yet foreseen occur.

Nuclear propulsion is a more complex issue. Clearly, interest in this alternative should not be viewed as energy-motivated, for as long as significant U.S. fossil fuel reserves (petroleum, coal, or oil shale) are

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[a]The notable exception may be the use of liquid hydrogen for hypersonic (and perhaps supersonic) vehicles. Such R&D should be motivated, however, by a requirement for a flight vehicle capable of hypersonic speeds rather than by the presumption that in this time frame LH_2 will prove to be a substitute for present-day applications of liquid hydrocarbon fuels. In this instance, the research objectives might be considerably different from those motivated by a large, subsonic airplane application (e.g., use of LH_2 for structural cooling).

available,[a] nuclear propulsion is not a particularly attractive competitor of JP-fueled airplanes in most mission applications. Nonetheless, several mission applications do exist for which nuclear propulsion's unique performance characteristics make it an attractive option. But R&D on nuclear-powered airplanes should proceed only if a firm requirement evolves for these missions; thus far, no such requirement has been identified. In any event, basic research that would eventually be useful to an airborne reactor program is warranted. Specifically, the materials problem within the reactor heat-exchanger systems may require substantial advances in the current state of the art. Of course, extensive development of nuclear aircraft propulsion should only proceed if research demonstrates that public safety can be assured. Research is necessary not only on technological problems but also on the political issues associated with the acceptance of nuclear aircraft. The difficulties encountered with nuclear submarines and the ways these difficulties were overcome should provide some guidance for implementation of a nuclear airplane fleet. Furthermore, how the public eventually accepts the civilian nuclear reactor programs should provide a barometer of possible attitudes toward nuclear aircraft.

Air Force R&D on future aviation fuels should concentrate almost exclusively on synthetic JP derived from oil shale or coal. Although this may at first seem to be a comforting outcome (since synthetic JP and JP-4 or JP-8 from crude oil will probably have similar properties), significant research will still be required. Of principal importance is the problem of assuring an adequate JP supply in the coming years. Because sufficient fossil-fuel reserves are available and can be economically exploited for the synthesis of jet fuel does not necessarily mean that the JP will be available when needed. For example, if ERDA were to place an early emphasis on the development of processes aimed at providing clean boiler fuels (which are generally not suitable for

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[a] At the largest credible rates of consumption, even current economically recoverable U.S. coal reserves could not be reduced by more than 50 percent before 2025 [19]. Thus, aircraft entering the inventory in the late 1990s can be assured of an adequate fossil resource base throughout their life cycle.

refining to jet fuels), then processes yielding premium syncrudes for transportation uses may not be developed in a timely manner. Therefore, an analysis of the available Air Force options for assuring the future availability of JP is required.

Significant technical work is also required. Limited experience to date indicates that refining synthetic crude oil to meet the exact specifications of JP-4 or JP-8 is likely to be expensive. Obviously, trade-offs between relaxing the Air Force's fuel specifications (with the attendant implications for airplane performance) and improving the refining process through advanced development should be examined. In addition, further consideration should be given to a multifuel engine --that is, an engine capable of operating on JP-4, JP-8, or a synthetic JP (from oil shale or coal) that might be refined to relaxed specifications. Again, pertinent trade-offs should be explored. In Ref. 19, these technical aspects of synthetic JP for military use are more thoroughly discussed and detailed recommendations are made.

VERY LARGE AIRPLANES

The Air Force should maintain a strong and active interest in advanced-technology large airplanes and should consider pursuing the R&D required to ensure that such an aircraft will be available. Needed work includes additional system design studies as well as research and development on specific aircraft technologies.

Aircraft System Design

The most important question that must be addressed through further system design work is: *What performance characteristics should an advanced-technology large airplane have in order to provide the greatest compatibility with military requirements and the available resources?*

Primary Mission Considerations. Since the primary Air Force mission requirement is almost certainly for a strategic airlifter, the most important items to be defined are:

- The design point (i.e., the design payload and associated design range).
- The cargo compartment dimensions.

These can be identified by developing a family of modest-fidelity conceptual designs (representing various design points, etc.) and then exploring their suitability in a detailed applications analysis where cost and effectiveness are explicitly taken into account. The conceptual design that provides a capability most closely attuned to Air Force requirements thus defines the optimum performance characteristics.

Numerous secondary design considerations also should be evaluated. These include:

- What are the appropriate takeoff- and landing-field length requirements?
- What are the appropriate runway bearing constraints?
- Should both front and rear loading be provided?
- Should the cargo compartment floor be at truck-bed height during loading?

Although such studies may be complex, they are manageable.[a]

Multimission Considerations. Providing an advanced-technology large airplane with a multimission capability will complicate the analyses recommended above. In Section II, we observed that the desirability of this capability is basically predicated on spreading the development costs over a larger number of airframes and lowering the average unit flyaway costs through learning-curve effects.

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[a]Two design considerations discussed in Section II and notably absent from this list are cruise Mach number and initial cruise altitude. The latter is largely determined by immutable facts of nature; thus, 30,000 ft is difficult to argue against. Although the cruise Mach number is more subtle, all available analyses indicate that 0.78 to 0.80 is reasonable. These should be examined in future design studies, but defining the other design constraints described above is, in our view, of far greater importance.

Although our analysis indicated that the VLA-JP could probably be justified in terms of cost-effectiveness on the basis of the strategic airlift mission alone,[a] the overall attractiveness of such a weapon system would be powerfully enhanced by the benefits that should accrue from a multimission capability.

Two classes of potential secondary missions exist and they are not necessarily mutually exclusive. The first is to employ the advanced-technology large airplane in commercial aviation as an air-cargo carrier. Beside the cost benefits mentioned, these commercial airplanes could be part of the CRAF fleet and provide additional wartime or emergency airlift capability.

The major question which must be addressed is: Is it possible to achieve a reasonable compromise between the diverse requirements of military and commercial cargo airplanes? The Deputy for Development Planning, Aeronautical Systems Division (ASD/XRL), is currently funding an "Innovative Aircraft Design" study, which will examine conceptual designs of several advanced-technology large airplanes at several design points. A primary objective of this work will be to assess the practicality of a common military-commercial cargo airplane. Thus, it should address several of the study areas recommended above.

The second multimission possibility is to utilize these airplanes in what we have termed the station-keeping role. Several potential mission applications seem particularly interesting:

- o Tactical battle platform
- o Maritime air cruiser
- o Strategic missile carrier

The present study has shown that an advanced-technology large airplane --procured under multimission assumptions--may be substantially more attractive than any contemporary equipment in these applications.

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[a]We believe it is axiomatic that an airplane designed as a strategic airlifter should also be capable of serving as an aerial tanker. To do otherwise would greatly decrease the utility of the airplane in the strategic airlift role.

The next logical question to address is: Should any of these types of missions be performed by a large, subsonic airplane? Further studies should explore whether an advanced-technology large airplane can be effectively utilized to supplement or replace other ways of performing these missions and should also identify what airplane characteristics (e.g., size) would be most suitable in these applications.

Aircraft Technology

ASD's previously mentioned "Innovative Aircraft Design" study should provide much richer detail on needed aircraft-technology R&D since the conceptual designs will be prepared in greater depth. However, our experience in the present research has indicated that additional R&D in some technology areas should be considered.

Of course, any USAF R&D effort must be cognizant of related NASA efforts in this area. Specifically, NASA has recently begun a research and technology program on aircraft fuel conservation [72]--the major elements of which are:

- o Propulsion
  - Engine component improvement
  - Fuel-conservative engine
  - Turboprop
- o Aerodynamics
  - Fuel-conservative transport
  - Laminar flow control
- o Structures
  - Composites in primary aircraft structures

Anticipated funding for this program through 1985 is $670 million (in then-year dollars).

The NASA program, as presently structured, is very compatible with the needs of a USAF advanced-technology large airplane which could enter the inventory in the post-1985 time frame. The Air Force, therefore, should cooperate fully with the NASA effort where appropriate.

Several technology areas of possible benefit to large military airplanes may be particularly suitable for Air Force investigation, either because they are not being extensively supported by the NASA work or because they may become candidates for reduced funding if the commercial aviation community fails to show an interest in them.

Propulsion. Advancing the state of the art of aircraft turbine engine technology (e.g., increased turbine inlet temperature) is included in the NASA program. The importance of this work is undeniable for obvious reasons.

The NASA program also includes the consideration of turboprops. To date, the airlines remain cool toward the idea of switching back from jets to props--fearing massive passenger unacceptance. (Such unacceptance could probably be tolerated if all airlines introduced turboprops, but it certainly lessens the likelihood of any single airline's being a leader in its introduction.) Thus, NASA may ultimately assign the turboprop work a relatively low priority.

The turboprop, however, might be much more acceptable for Air Force (and/or commercial air cargo) application. One concept is particularly intriguing--the so-called "prop-fan" developed by Hamilton Standard. (This propellor-like device somewhat resembles a high bypass ratio turbofan with the shroud removed.) Work to date suggests that reductions in mission fuel requirements of 15 to 20 percent may be possible, and this at a cruise Mach number of 0.8 rather than the 0.60 to 0.65 typical for standard turboprops [73]. Such a potential payoff warrants at least cursory examination by the Air Force.[a] The first objective should be to determine whether efficiency improvements of this magnitude are, in fact, achievable.

Aerodynamics. Laminar flow control is also included in the planned NASA effort. Again, however, possible airline resistance to this essentially new technology could prove fatal. Furthermore,

[a]An interesting feature of the propfan (and propellors in general) is its intrinsically superior propulsive efficiency when operating at flight speeds less than the design maximum. This characteristic could provide very significant payoffs in missions that include extended loiter periods.

the available studies indicate that the benefits of laminar flow control are more significant for long-range aircraft (i.e., aircraft with ranges greater than 5500 n mi) [35,74]. Extreme range is probably of much greater interest to the Air Force than to the commercial sector. Therefore, the Air Force should monitor the NASA efforts (assisting where appropriate) and be prepared to continue the work should NASA de-emphasize laminar flow control--assuming, of course, that the concept remains technically and economically promising from a military viewpoint.

One additional aerodynamic technology item has not received a great deal of attention thus far: the potential applications of relatively thick supercritical wings (e.g., thickness ratios as large as 20 percent). The intent here is to permit a reduction in wing weight for cruise Mach numbers near 0.8 rather than to increase the cruise Mach number--the original goal of supercritical airfoil technology. Of course, supercritical airfoils also permit reductions in wing sweep (with a concomitant increase in the aerodynamic aspect ratio) for this cruise Mach number. Thus, trade-offs must be made among wing thickness, sweep, and aspect ratio to obtain an optimum M = 0.8 cruise configuration. Unfortunately, little is known, either theoretically or from experimental data, about the characteristics of thick supercritical sections.[a] A relatively modest research program would indicate whether the potential of thick supercritical wings merits more intensive theoretical and experimental investigations.

Structures. The principal advances in aircraft structures center on the possible use of composite materials in primary structure. Again, the NASA work and related Air Force efforts seem sufficient--with a notable exception. Recent studies have indicated that the attenuation characteristics of composites with respect to electromagnetic waves are markedly different from those of the commonly used metal alloys [75]. The consequences of this may be of great importance. For example, composite material would afford little, if any, protection from lightning strikes. Because of the very substantial weight-saving

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[a]These types of airfoil sections could also be employed to great advantage in span-loader aircraft.

possibilities of composites, a vigorous R&L program on these potential problems is clearly required. (An interesting point is that if using composites in primary structure proves impractical, the potential benefits of advanced aerodynamic technologies, such as laminar flow control, would become increasingly important. These technologies provide a much greater payoff when applied to an all-aluminum airplane than when applied to one incorporating composites.)

Finally, additional research on the aeroelastic implications of high-aspect ratio wings is needed. Some work in this area will undoubtedly be included as part of NASA's effort on fuel conservative transports.

Appendix A

VERY LARGE AIRPLANE DESIGN ANALYSIS

This appendix summarizes the results of the conceptual aircraft design analysis accomplished under the Deputy for Development Planning, Aeronautical Systems Division (ASD/XR). The objective of this analysis was to investigate the physical and operational characteristics of very large airplanes, i.e., airplanes with greater than one million pounds takeoff gross weight (TOGW), designed to use alternative fuels.

In all, six baseline aircraft were designed for primary operation as strategic airlifters; but these could easily be modified to serve as tankers. Four of the aircraft were designed to deliver 350,000 lb of payload a distance of 3600 n mi, off-load, and return empty without refueling (i.e., a 3600 n mi radius mission). Each of these aircraft inherently possessed the capability to deliver 350,000 lb of payload on a range in excess of 6000 n mi, and each utilized a different fuel: conventional hydrocarbon jet fuel (VLA-JP), liquid methane (VLA-LCH_4), liquid hydrogen (VLA-LH_2), and nuclear power (VLA-NUC). The remaining two aircraft designs, an excursion-case liquid hydrogen aircraft (designated VLA-LH_2*) and an excursion-case nuclear-powered aircraft (designated VLA-NUC*), were developed in order to investigate for these fuels aircraft designs which had approximately the same takeoff gross weights as the baseline VLA-JP design.

Table A-1 shows the breakdown by weight group for each of the six aircraft designs developed in this study. Additional details of the propulsion system weights are presented in Appendix B.

These weights were computed from statistical equations. We should note, however, that the size of the aircraft examined in this study is far outside the data base from which the statistical weight prediction equations were derived.

An additional potential application of these aircraft is the tanker role for the in-flight refueling of tactical fighters, strategic

Table A-1

GROUP WEIGHT STATEMENTS FOR THE ALTERNATIVE AIRPLANES
IN THEIR CARGO CONFIGURATION
(lb)

Weight Group	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Wing	265,210	307,250	187,542	552,679	256,770	365,764
Tail	41,866	42,240	21,776	71,522	29,565	52,814
Fuselage	251,327	265,138	286,649	284,299	348,227	202,692
Gear	73,068	73,928	53,223	110,262	65,541	83,849
Surface controls	12,374	12,369	9,210	17,252	10,772	13,847
Nacelle and pylon	16,081	16,475	10,867	25,377	14,025	18,241
Propulsion	(94,280)	(115,993)	(99,301)	(810,217)	(144,899)	(639,517)
Engine	73,158	75,259	46,131	131,503	62,326	90,898
Thrust reversers	12,583	12,945	7,935	22,356	10,720	15,453
Fuel system	8,538	27,789	45,235	4,841	71,853	3,610
Nuclear systems	---	---	---	651,517	---	529,556
Auxiliary power unit	966	966	966	966	966	966
Instruments and navigation	1,482	1,482	1,465	2,134	1,552	1,905
Hydraulic and pneumatic	3,740	3,740	3,663	4,323	4,081	3,493
Electrical	4,844	4,844	4,807	5,110	5,002	4,724
Avionics	2,652	2,652	2,652	2,652	2,652	2,652
Furnishing and equipment	6,110	6,110	6,110	6,110	6,110	6,110
Air cond. and anti-ice	7,220	7,220	7,220	7,220	7,220	7,220
Auxiliary gear	308	308	308	308	308	308
Empty weight	781,527	860,714	695,738	1,900,430	897,690	1,404,101
Operating empty weight	793,593	872,342	703,758	1,906,545	909,912	1,409,189
Usable fuel	695,402	641,658	221,242	403,455	287,088	300,811
Payload	350,000	350,000	350,000	350,000	425,000	230,000
Maximum gross weight	1,839,000	1,864,000	1,275,000	2,660,000	1,622,000	1,940,000
AMPR[a] weight	634,463	691,506	553,647	1,017,912	703,540	706,106

[a]Aircraft Manufacturer's Planning Report.

bombers, etc.[a] Much of the refueling equipment could be removed from the aircraft for the cargo mission; however, some equipment would be permanently installed on the aircraft. Table A-2 provides the weight increments necessary to provide this additional aerial refueling capability. (The refueling system consists of two wing-mounted refueling stores and one fuselage-mounted store.)

The analysis was conducted using the preliminary aircraft design tools available within the office, Deputy for Development Planning, Aeronautical Systems Division. The Interactive Computer Aided Design (ICAD) program was the primary design tool for all areas of investigation, excluding propulsion systems, which were input to ICAD (see Appendix B). The major area of concern for this study was the accuracy of the structural weight estimation routines within ICAD. Some initial investigations, using more detailed structural analysis programs, have indicated that the structural weights computed may be optimistically low. This optimism could be offset by our assuming an all-aluminum structure. If advanced composites were considered, structural weight might be substantially reduced.

SUMMARY OF DESIGN CONSTRAINTS

Each of the aircraft was designed to achieve an 8000-ft critical field-length takeoff at maximum gross weight and each was designed to a structural load factor of 2.25 g. The cargo compartment was sized to be compatible with existing containerized loads as well as outsized equipment. This resulted in a maximum floor width of 25 ft, for compatibility with both military 463L pallets and 8 ft x 8 ft air/surface intermodal containers (see Section II).

The footprint pressure of each of the aircraft was restricted to being no greater than that experienced by a commercial aircraft of the 200,000-lb TOGW class. This was done to avoid either the necessity for major airfield modifications or undue restriction of the aircraft's utility.

[a] Here, we are assuming that in all cases JP is the fuel being transferred. Employment of the cryogenic-fueled alternatives for the in-flight refueling of airlifters using the same fuel is discussed in Appendix C.

Table A-2

WEIGHT INCREMENTS TO PROVIDE AN AERIAL REFUELING CAPABILITY
(lb)

Weight Increment	Design-Point VLAs	VLA-LH_2*	VLA-NUC*
Total nonremovable	(4,558)	(5,258)	(3,358)
Structure	390	390	390
Fuel system	3,908	3,908	3,908
Hydraulic system	140	140	140
Electric system	120	120	120
Total removable	(5,259)	(5,259)	(5,259)
Stores and booms	4,164	4,164	4,164
Operator provisions	315	315	315
Operators (3)	600	600	600
Trapped fuel	180	180	180
Total weight increment	9,817	10,517	8,617
Additional fuel capacity	344,741	419,741	224,741

NOTE: It is assumed in all cases that JP is the fuel being transferred and that the maximum gross weight remains unchanged from that shown in Table A-1.

The aircraft were designed on the basis of present technology (i.e., 1980 state of the art) and did not incorporate advanced-aerodynamic or structural-technology items other than the propulsion systems. Engine technology was assumed to have evolved sufficiently to permit growth versions, in terms of thrust and size of present turbofan engines (see Appendix B).

A typical mission profile consisted of a 5-minute warm-up at normal rated power (sea-level static operation), a climb from sea level to 30,000 ft at intermediate power, and a Mach 0.75 cruise at 30,000 ft. Fuel reserves were provided for a 200 n mi flight to an alternate base. No fuel or range credit was taken for descent and landing.

AIRCRAFT DESCRIPTION

A summary of the major aircraft design and performance characteristics is given here. The chemical-fueled alternatives are described first, then the nuclear-powered airplanes.

Design-Point Conventional Jet Fuel Aircraft (VLA-JP)

The general arrangement and size of the JP aircraft is shown on Fig. A-1 and a cross section of the fuselage on Fig. A-2. Both front and rear loading is provided, with complete drive-through capability; however, the drive-through capability was not considered to be a firm design constraint.

The range-payload trade-off characteristics of this aircraft are shown on Fig. A-3 and its radius-endurance characteristics on Fig. A-4. Observe that the range-payload curves for both the 2.5 g and 2.25 g load factors are depicted in Fig. A-4. Takeoff- and landing-field length characteristics are provided in Fig. A-5.

Design-Point Liquid-Methane Aircraft (VLA-LCH_4)

Liquid-methane, being a cryogenic fluid of much lower density than JP, requires a much larger fuel-tank volume than is normally available in the wings and this necessitated the design of a nonintegral fuel tank to be housed in the aircraft fuselage.

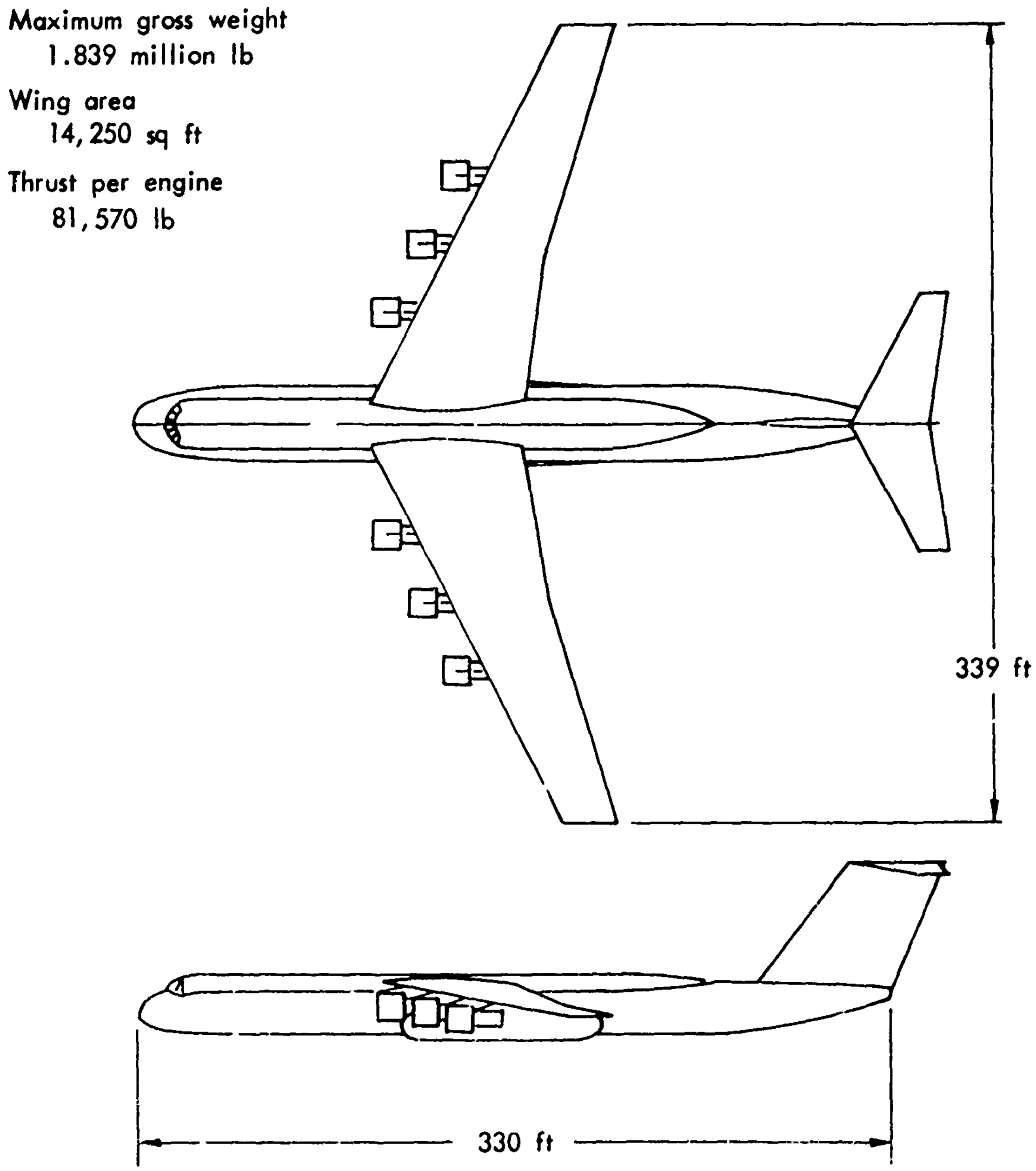

Fig. A-1 — General arrangement of the VLA-JP

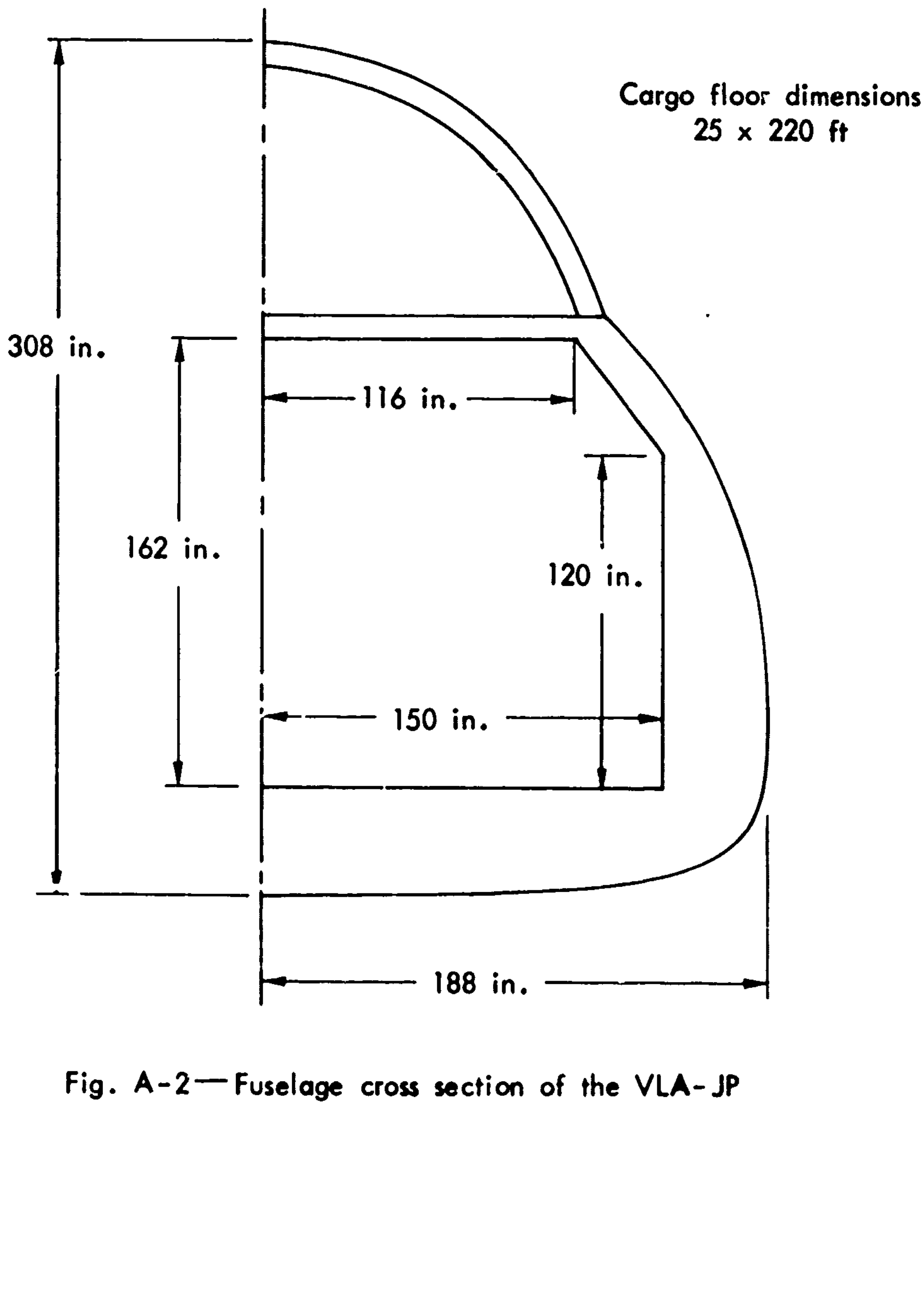

Fig. A-2—Fuselage cross section of the VLA-JP

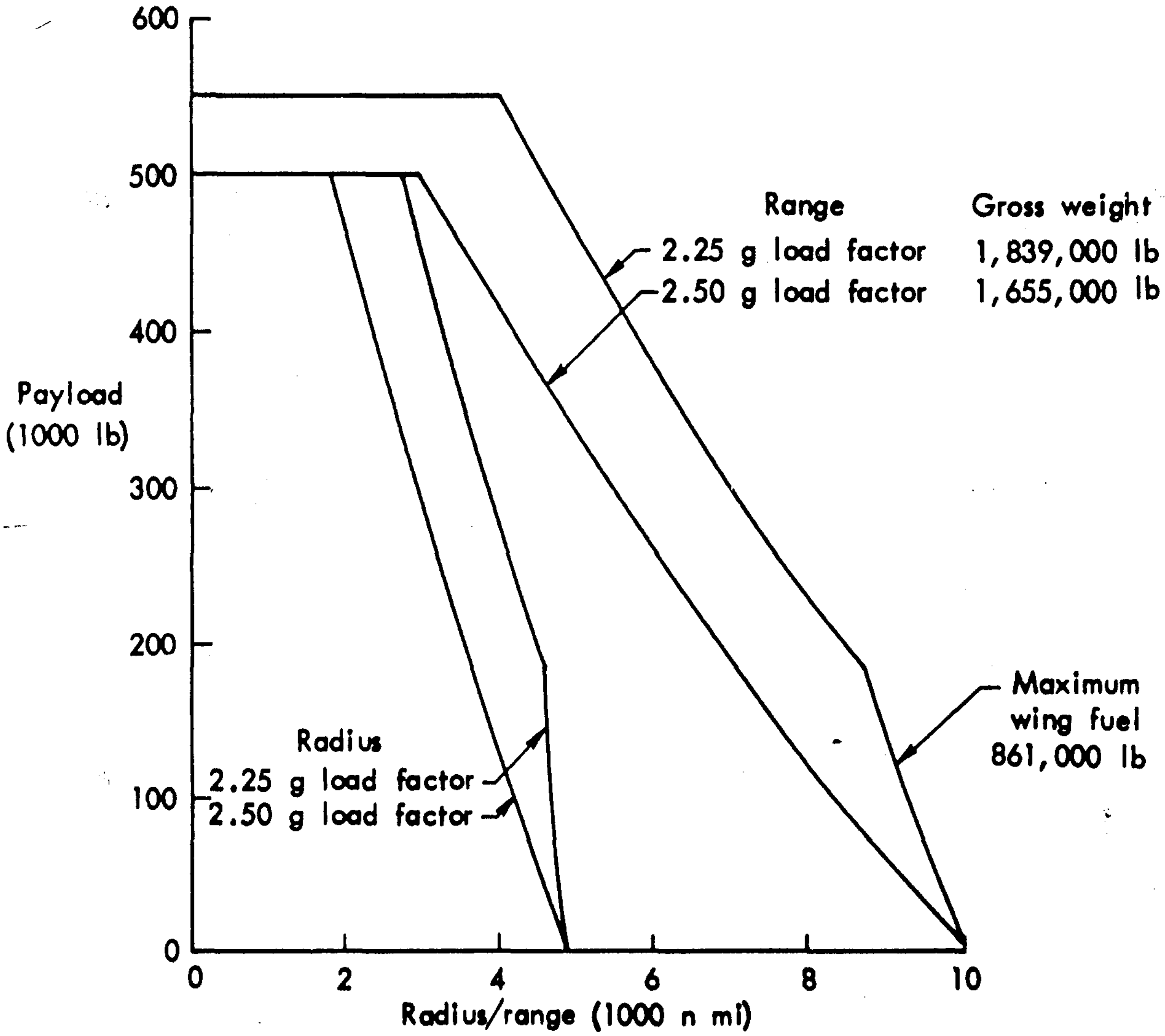

Fig. A-3—Payload characteristics of the VLA-JP in terms of mission range or radius

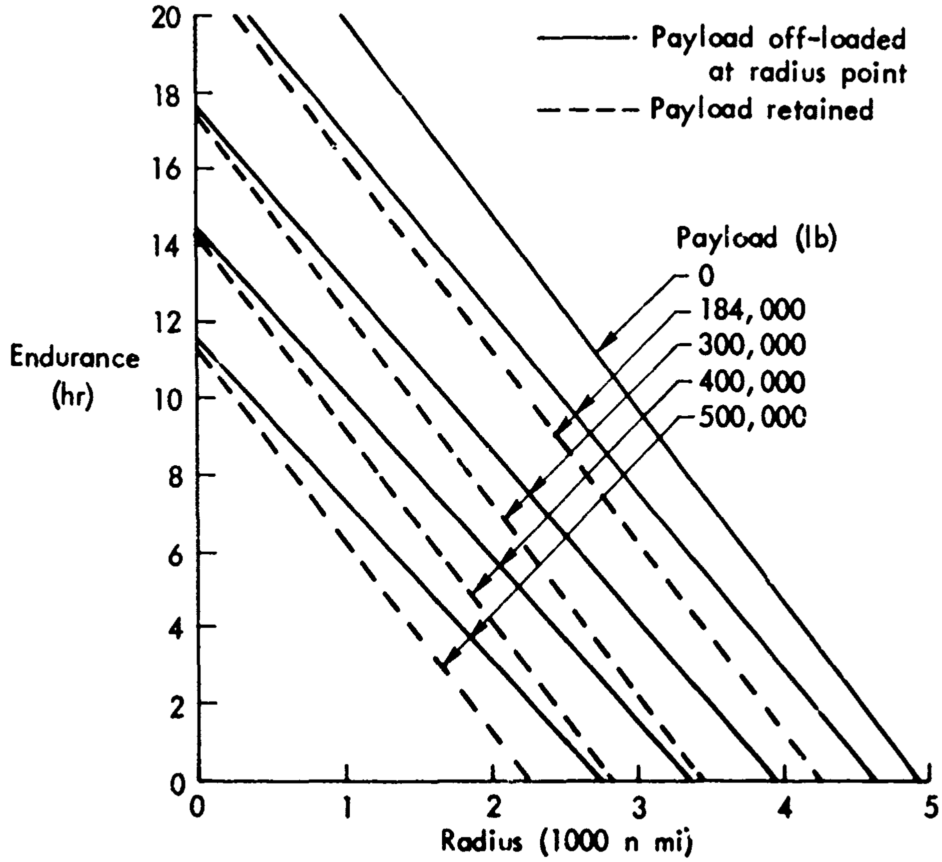

Fig. A-4—Endurance characteristics of the VLA-JP

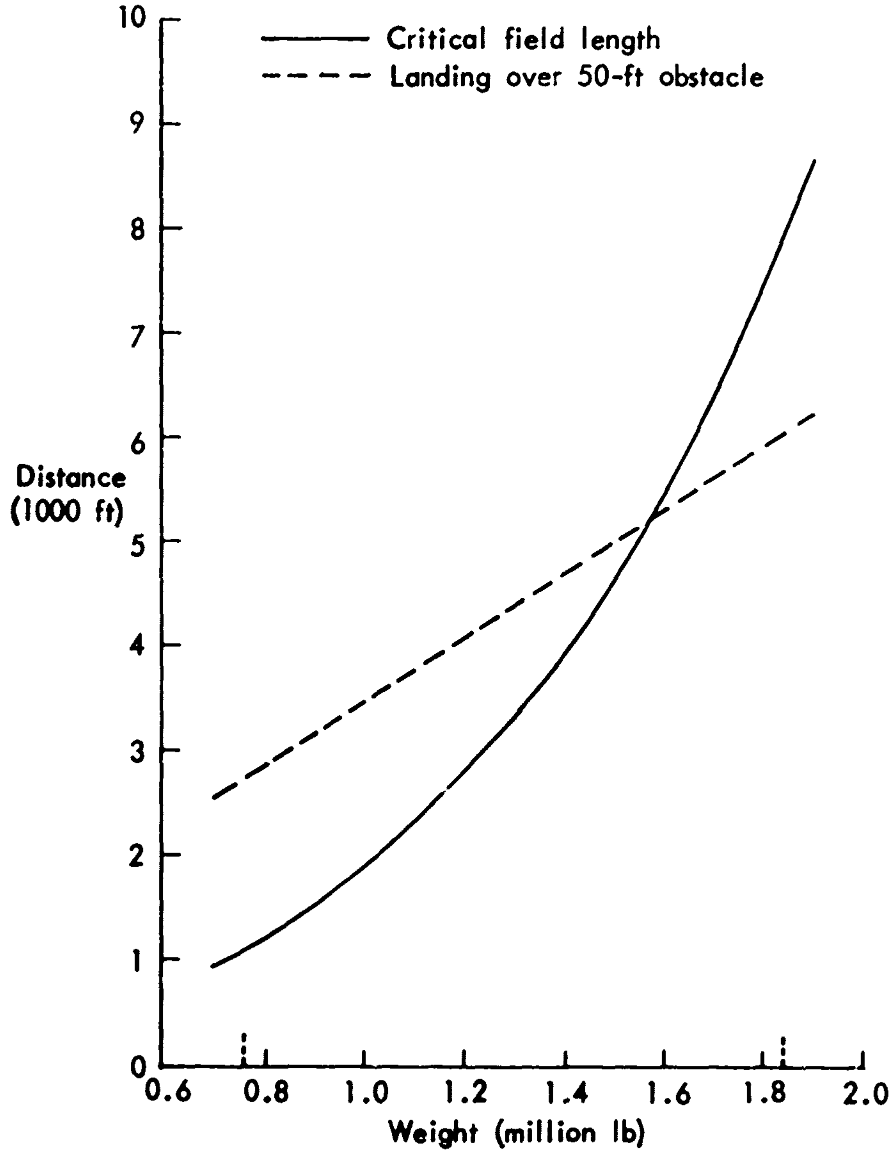

Fig. A-5—Field-length characteristics of the VLA-JP

A study was conducted to determine a near-optimum shape for these cryogenic tanks. The selected cross section was a double-bubble arrangement with each bubble a circular arc. The selected tank height to width ratio was 2/3, and this allowed for minimum fuselage wetted area. The tank was designed for an assumed gauge pressure of one atmosphere and consisted of an aluminum shell with a 3-in. outside layer of foam insulation. Two such tanks were required, one located immediately forward and one immediately aft of the wing carry-through structure.

The loss of the relieving loads in the wings normally contributed by the fuel was expected to result in a significant increase in the weight of the wing structure required. However, the existing analysis technique which was based upon extrapolated data was not adequate to evaluate thoroughly the additional weight increment required, and so an estimated increment of 15 percent was arbitrarily added.

Figures A-6 and A-7 show the general arrangement of the liquid-methane-fueled aircraft. The payload capacity (in terms of radius/range) for the liquid-methane aircraft is shown on Fig. A-8 and its radius-endurance characteristics on Fig. A-9. Takeoff and landing distances are depicted in Fig. A-10.

Design-Point Liquid-Hydrogen Aircraft (VLA-LH_2)

Figures A-11 and A-12 illustrate the general arrangement of the liquid-hydrogen-fueled aircraft. The cryogenic fuel tanks were similar to those of the VLA-LCH_4 aircraft, but the LH_2 tanks are mounted entirely above the primary fuselage structure. A fairing is placed over them to reduce aircraft wetted area and to provide an attachment to the primary fuselage structure.

Figure A-13 shows the payload versus radius/range plots for the VLA-LH_2 aircraft; endurance characteristics are shown in Fig. A-14. Note that these results are significantly different from those of the VLA-JP, primarily because of the differences in heating value and density of the two fuels. For example, if the payload of the VLA-LH_2 aircraft is increased above 350,000 lb, fuel must be removed to maintain a constant gross weight (i.e., the maximum gross weight). Since LH_2 has a very high energy content per pound of fuel, the removal of this

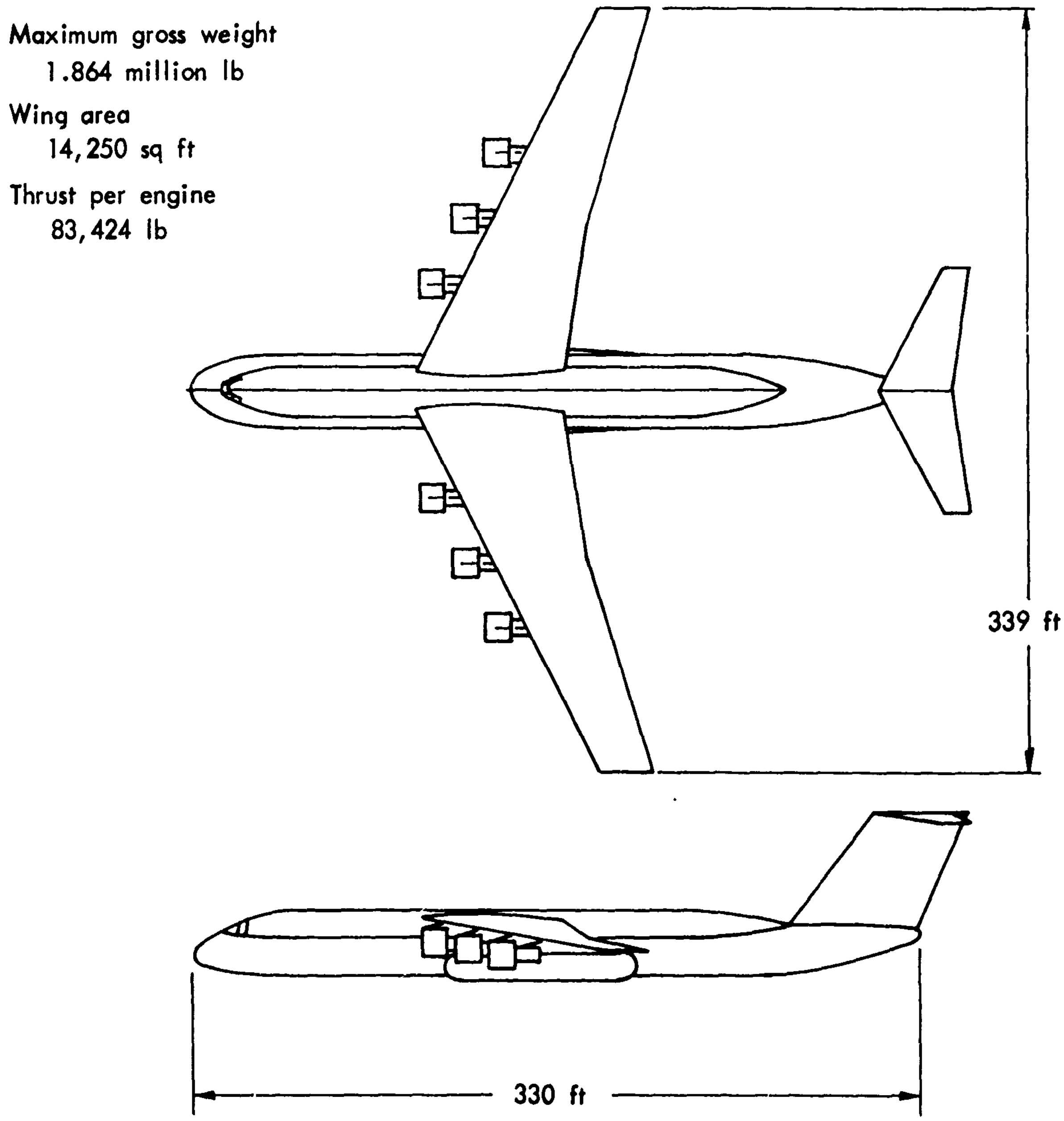

Fig. A-6—General arrangement of the VLA-LCH_4 aircraft

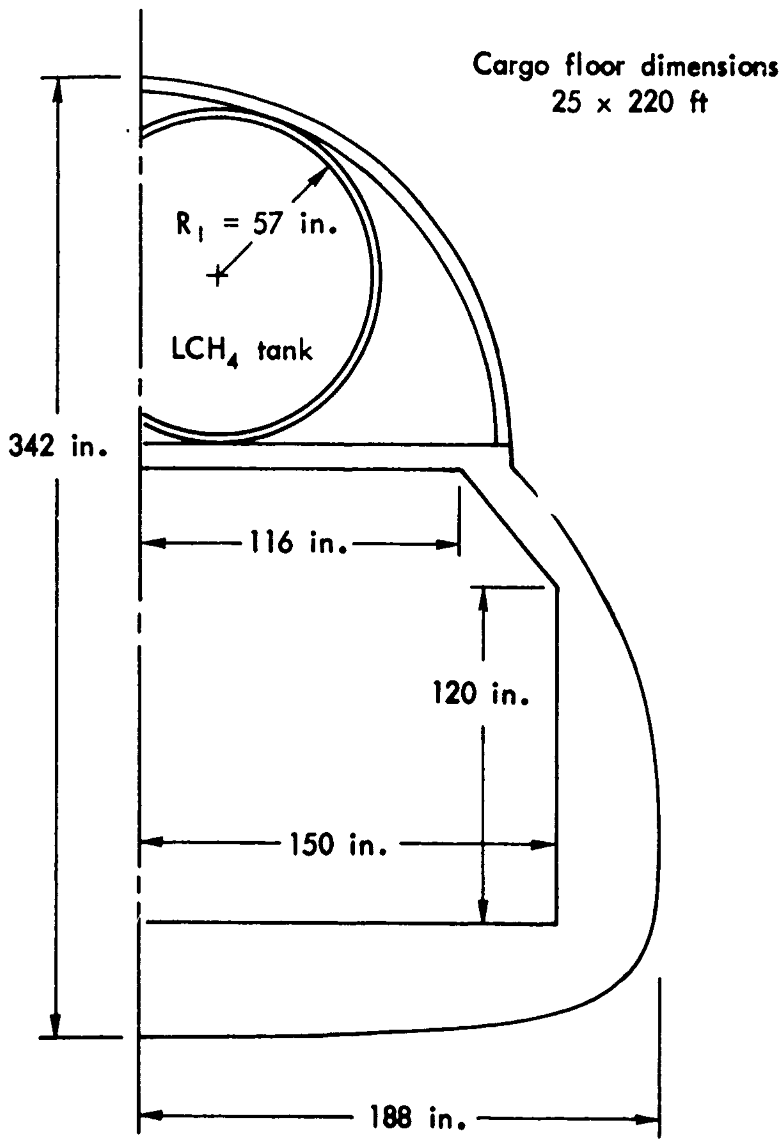

Fig. A-7—Fuselage cross section of the VLA-LCH_4

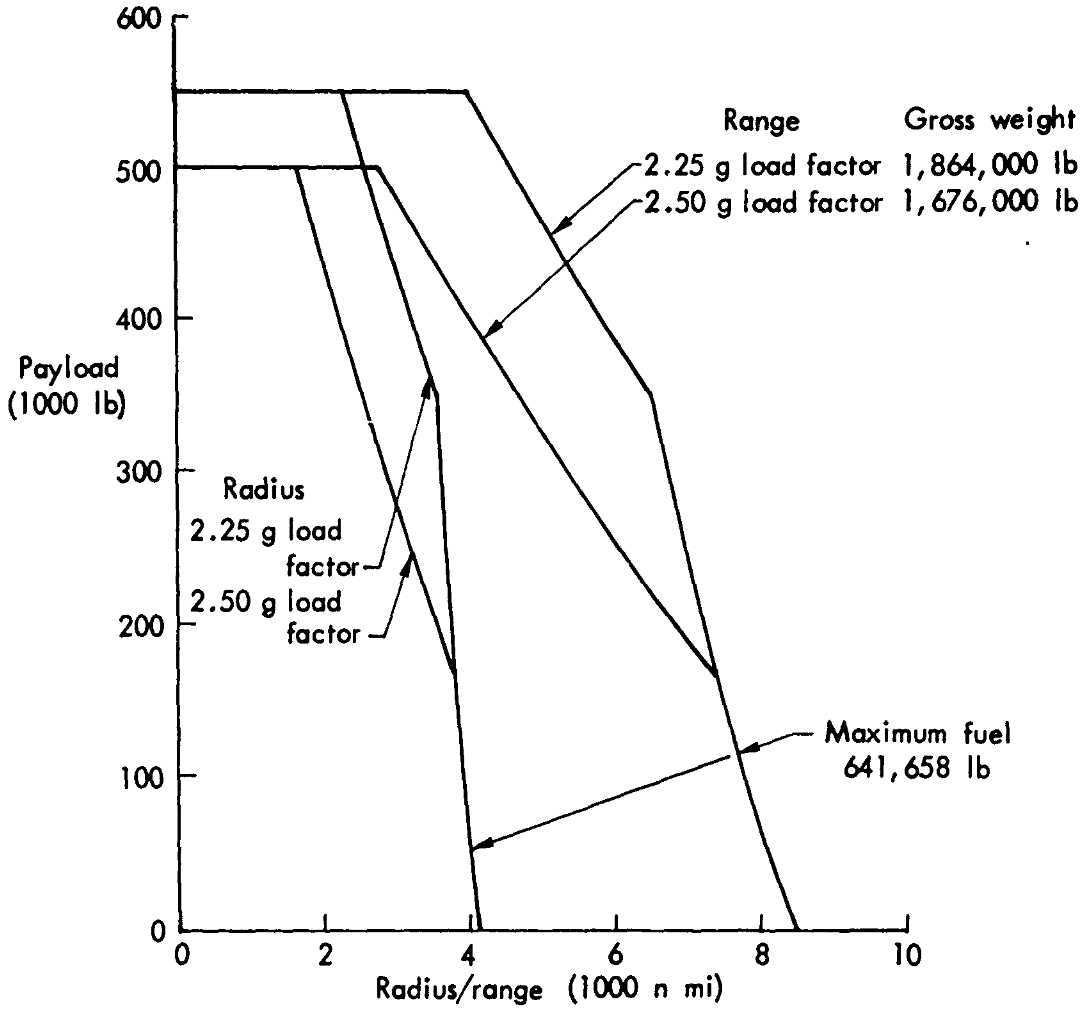

Fig. A-8 — Payload characteristics of the VLA-LCH_4 in terms of mission range or radius

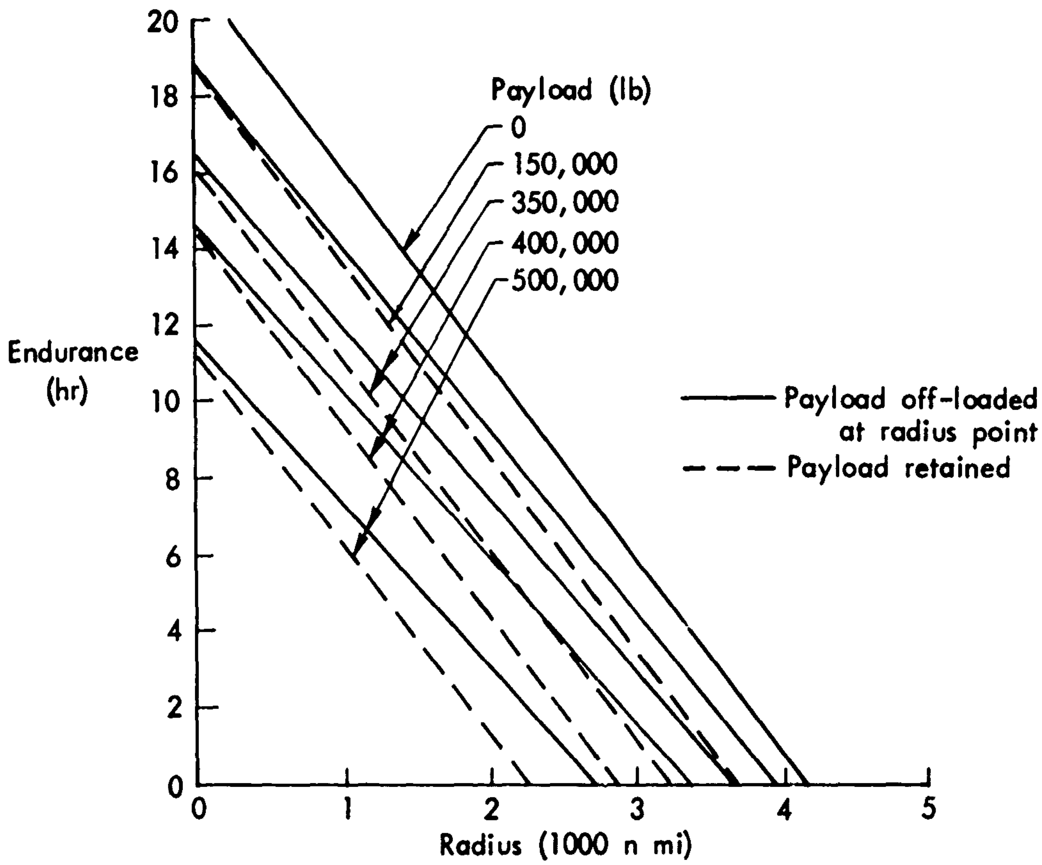

Fig. A-9—Endurance characteristics of the VLA-LCH_4

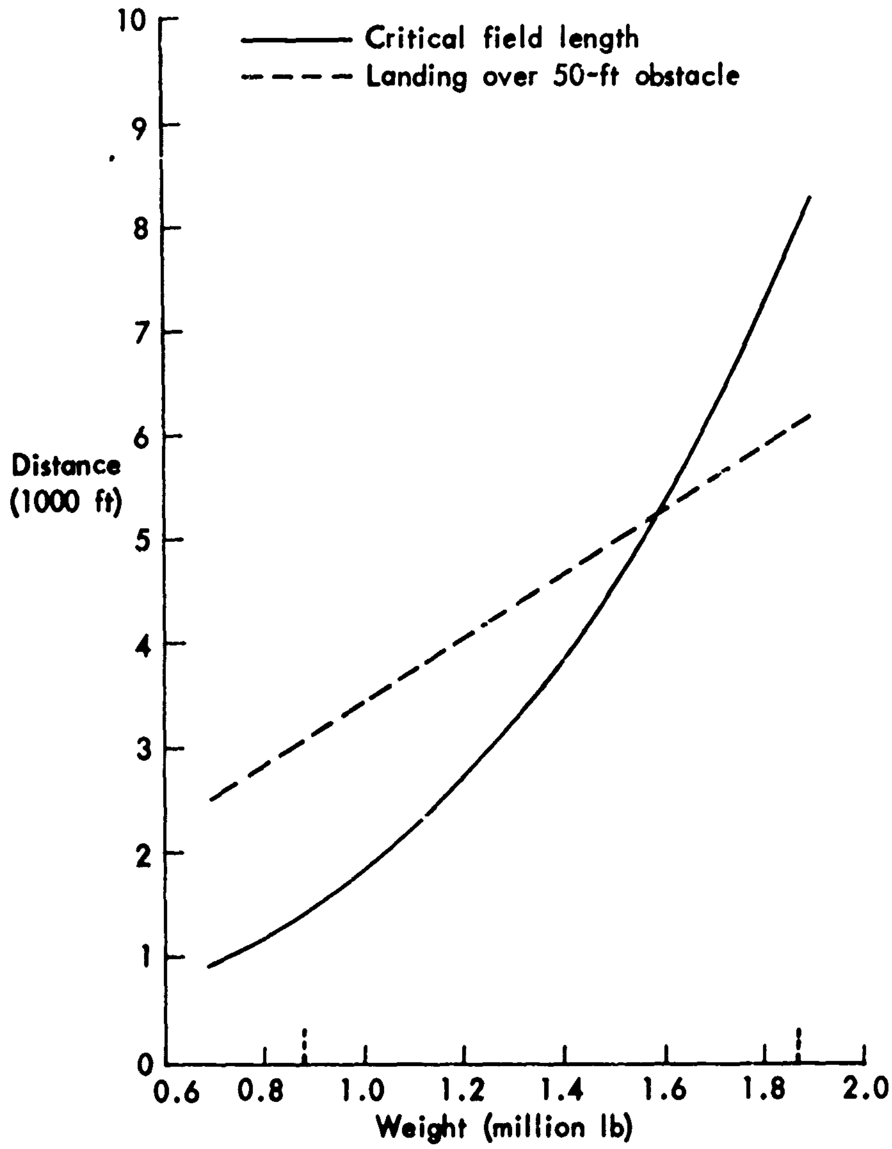

Fig. A-10—Field-length characteristics of the VLA-LCH_4

Maximum gross weight
1.275 million lb

Wing area
9,808 sq ft

Thrust per engine
56,395 lb

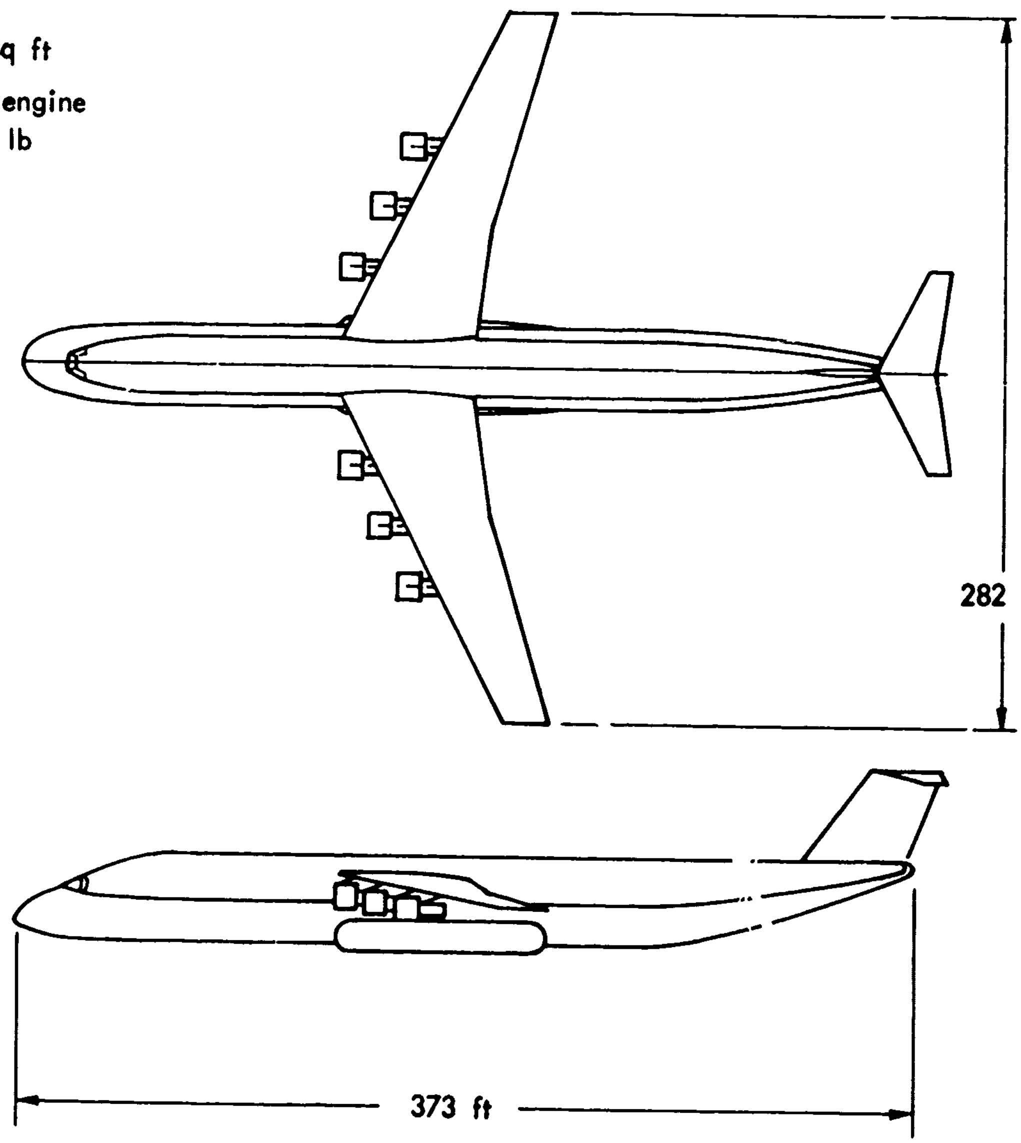

Fig. A-11—General arrangement of the VLA-LH_2

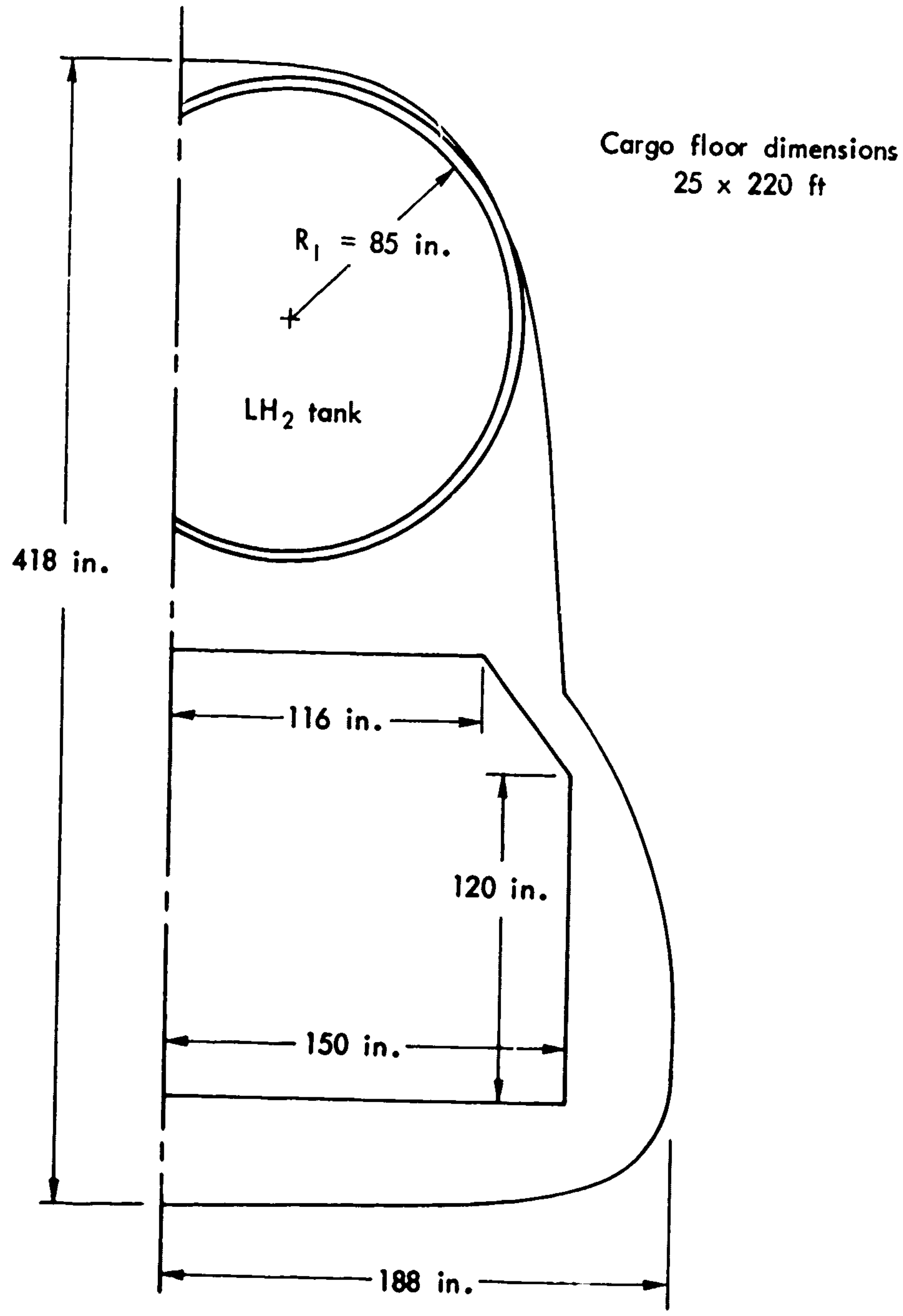

Fig. A-12—Fuselage cross section of the VLA-LH_2

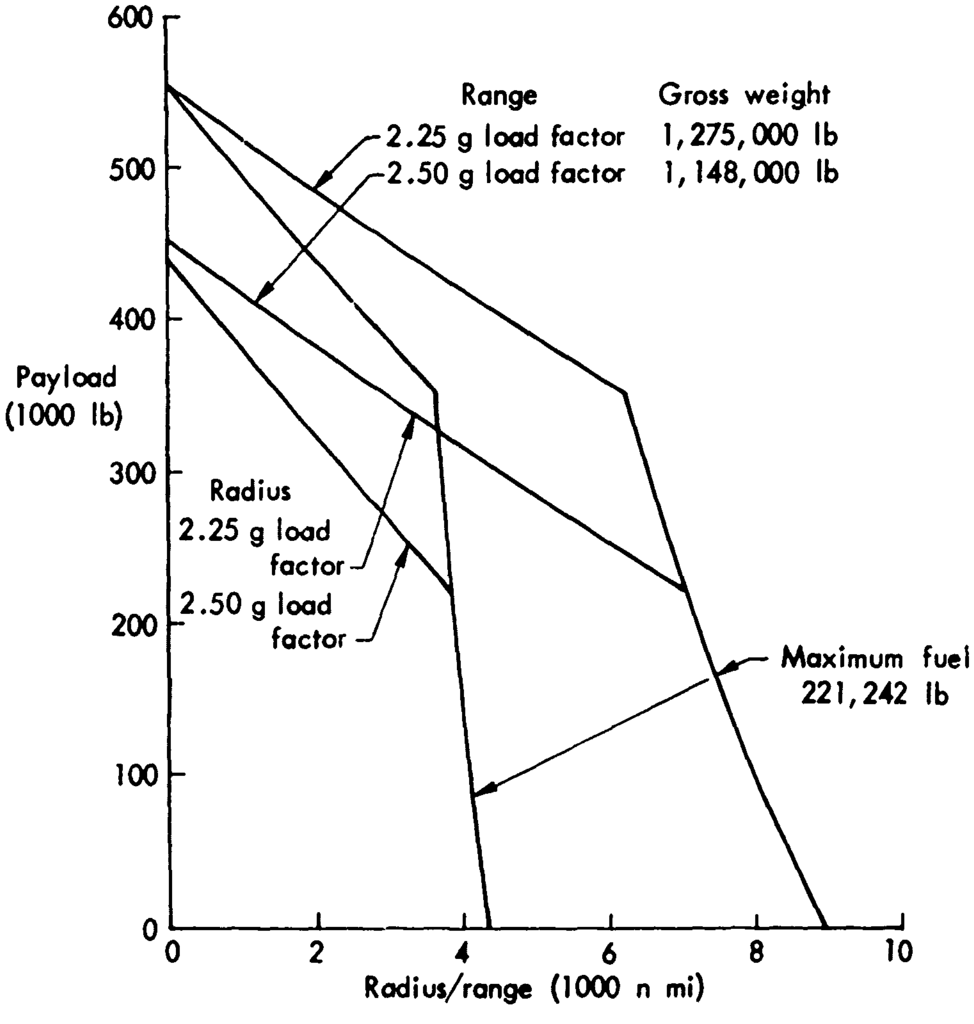

Fig. A-13—Payload characteristics of the VLA-LH_2 in terms of mission range or radius

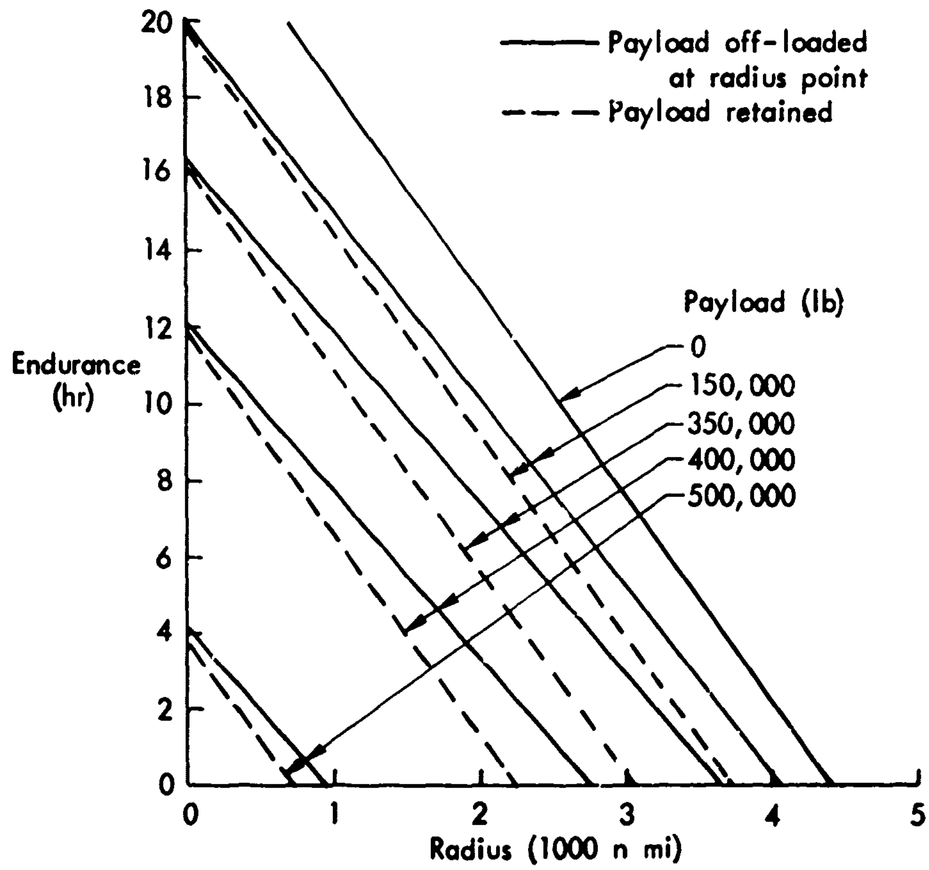

Fig. A-14—Endurance characteristics of the VLA-LH_2

fuel will cause a significant loss in range or radius capability. Conversely, if the payload is reduced from 350,000 lb to some lower value, the fuel onboard cannot be increased to maintain the maximum gross weight, since the fuel tank is filled to capacity at a payload of 350,000 lb. As a result, the VLA-LH_2 aircraft range/radius capability is equal to that of the VLA-JP aircraft at only the design payload of 350,000 lb. For any other payload, the LH_2 has less range/radius capability than the JP aircraft.

Figure A-15 displays the takeoff and landing characteristics of the VLA-LH_2 aircraft. Note that these results are comparable to those of the VLA-JP aircraft. However, the lower maximum gross weight of the LH_2 alternative would facilitate improvements to its takeoff/landing characteristics—through increased thrust loadings—if such were desirable.

Excursion-Case Liquid-Hydrogen Aircraft (VLA-LH_2*)

In order to examine a liquid-hydrogen-fueled airplane that approximated (or exceeded) the payload capabilities of the VLA-JP aircraft at any range/radius, an alternate liquid-hydrogen aircraft design (designated VLA-LH_2*) was developed that had approximately the same maximum gross weight as the JP aircraft. The configuration of this aircraft is shown in Figs. A-16 and A-17. Figure A-18 provides the payload radius/range capability of this aircraft; Fig. A-19 shows its radius/endurance characteristics, and Fig. A-20 gives its takeoff/landing characteristics.

Observe that the cargo floor area of the VLA-LH_2* aircraft is about 20 percent greater than that of the JP aircraft. This allows the cargo floor loading on a 3600 n mi radius mission to be approximately the same for both aircraft. In addition to the longer cargo floor, the equivalent fuselage diameter was increased to accommodate the much larger liquid-hydrogen fuel tanks.

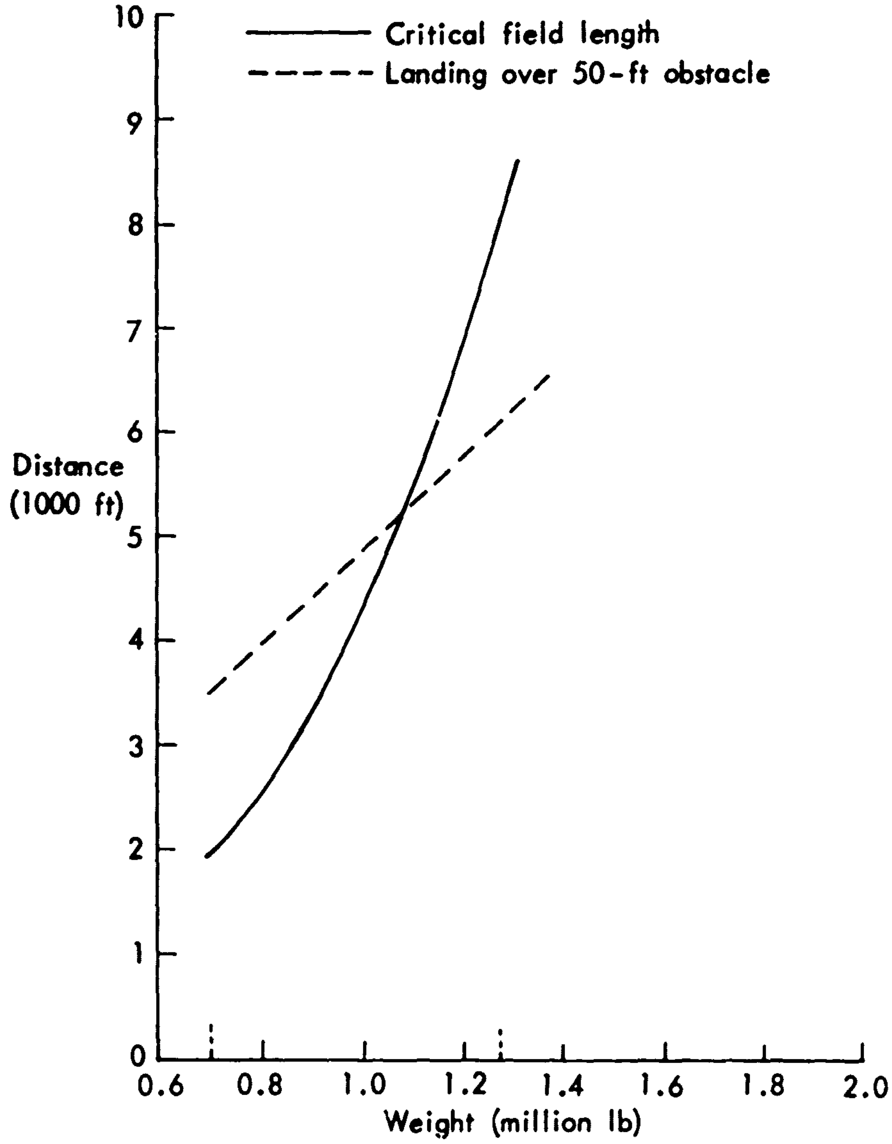

Fig. A-15—Field-length characteristics of the VLA-LH_2

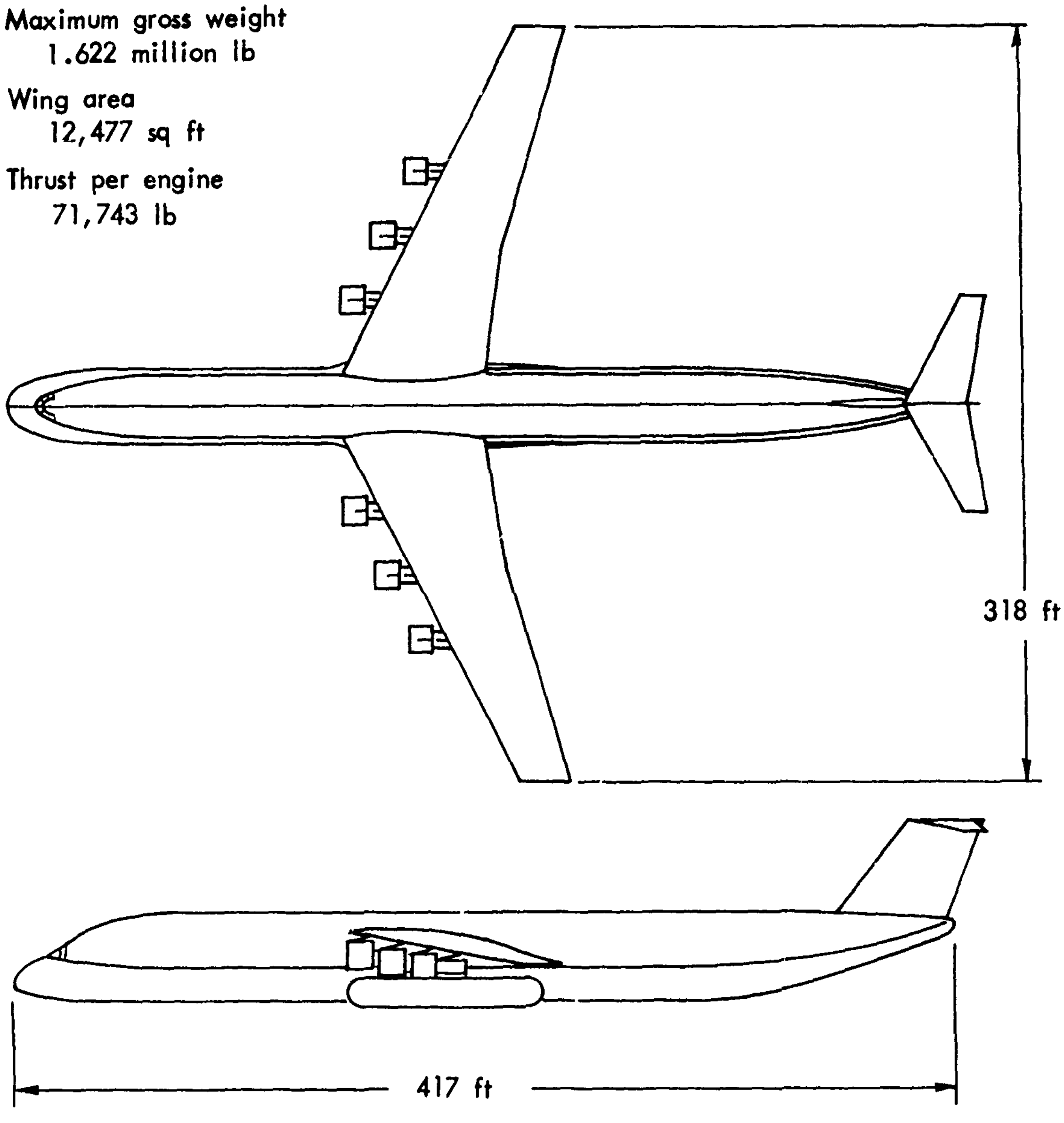

Fig. A-16—General arrangement of the VLA-LH_2*

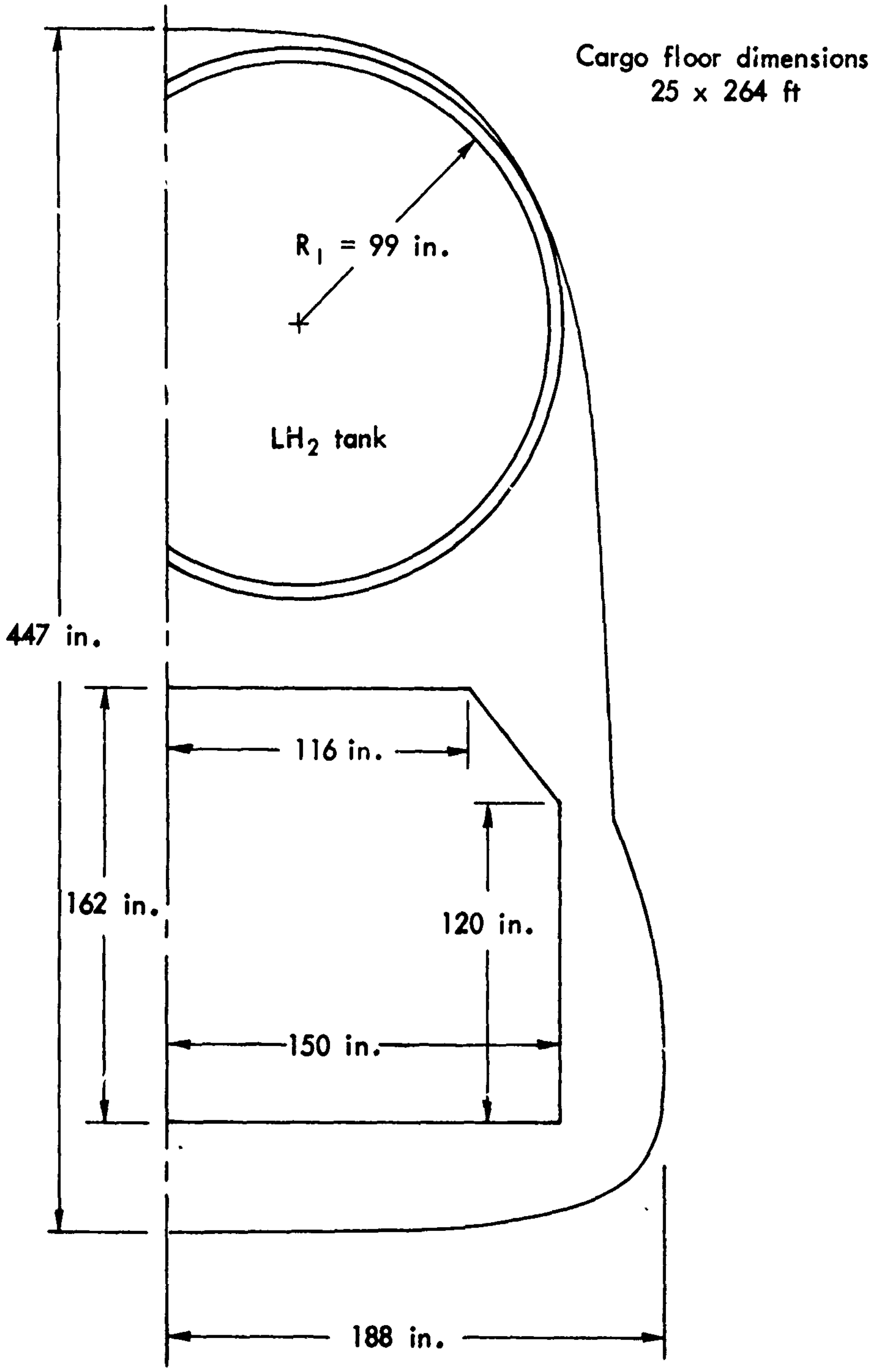

Fig. A-17—Fuselage cross section of the $VLA-LH_2$*

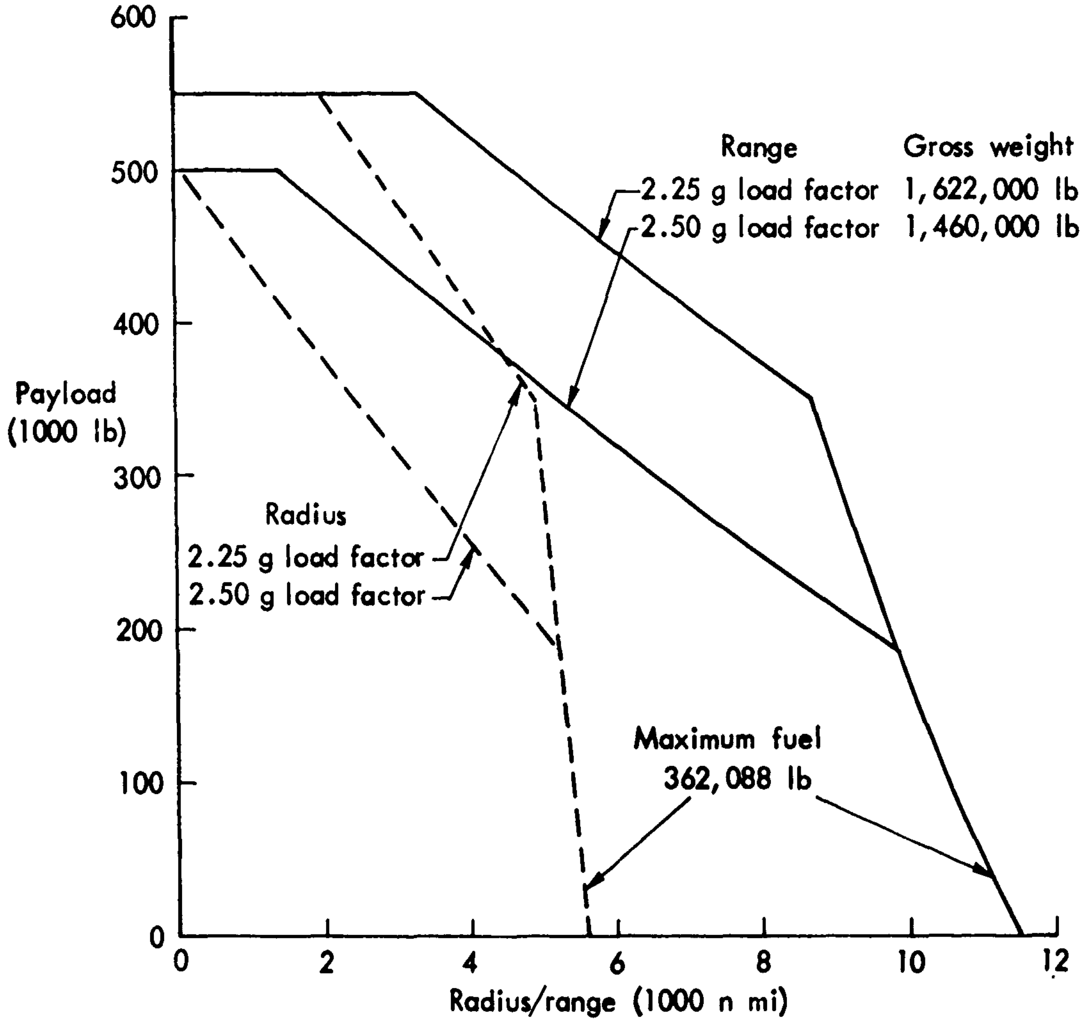

Fig. A-18—Payload characteristics of the VLA-LH_2*
in terms of mission range or radius

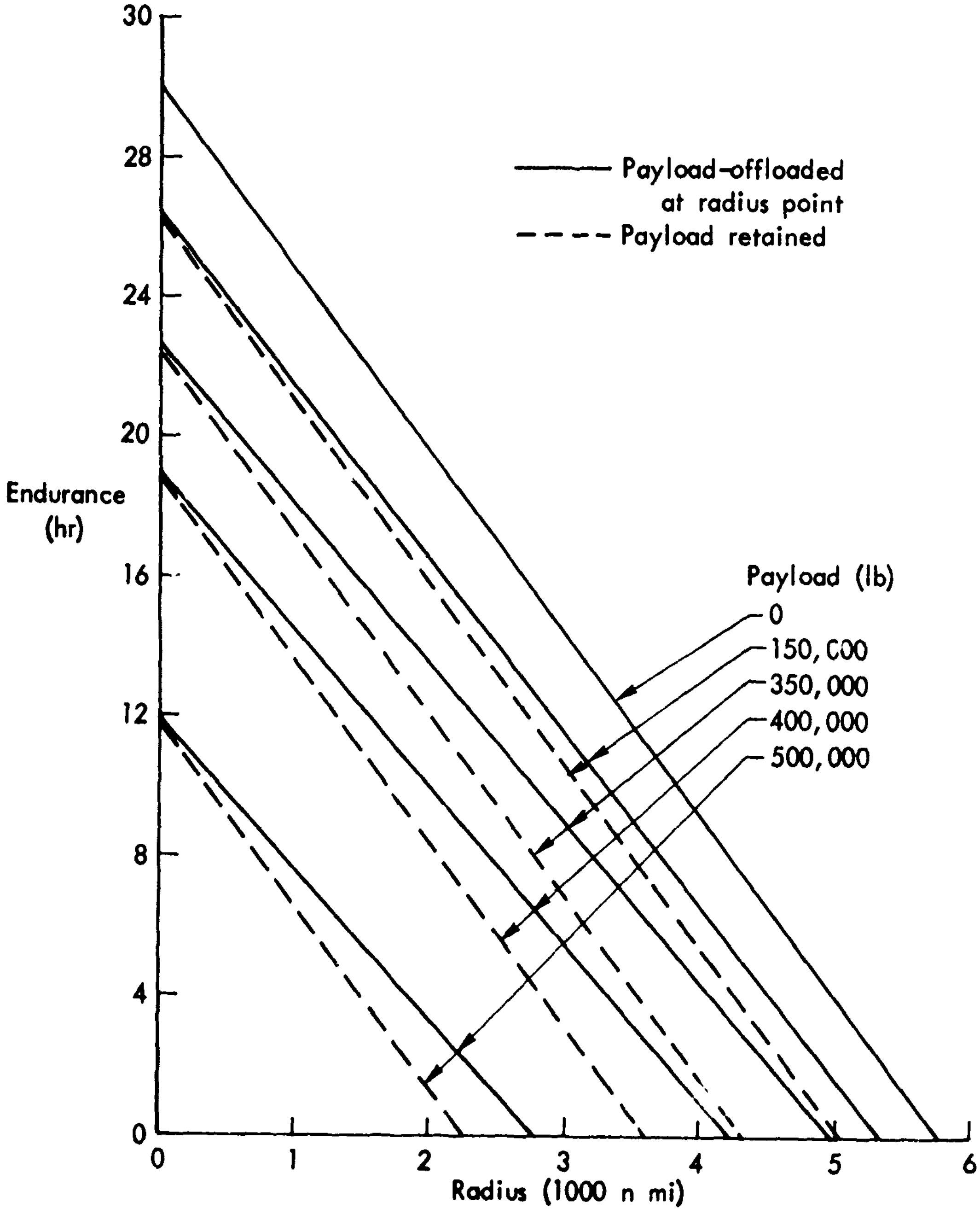

Fig. A-19—Endurance characteristics of the VLA-LH_2*

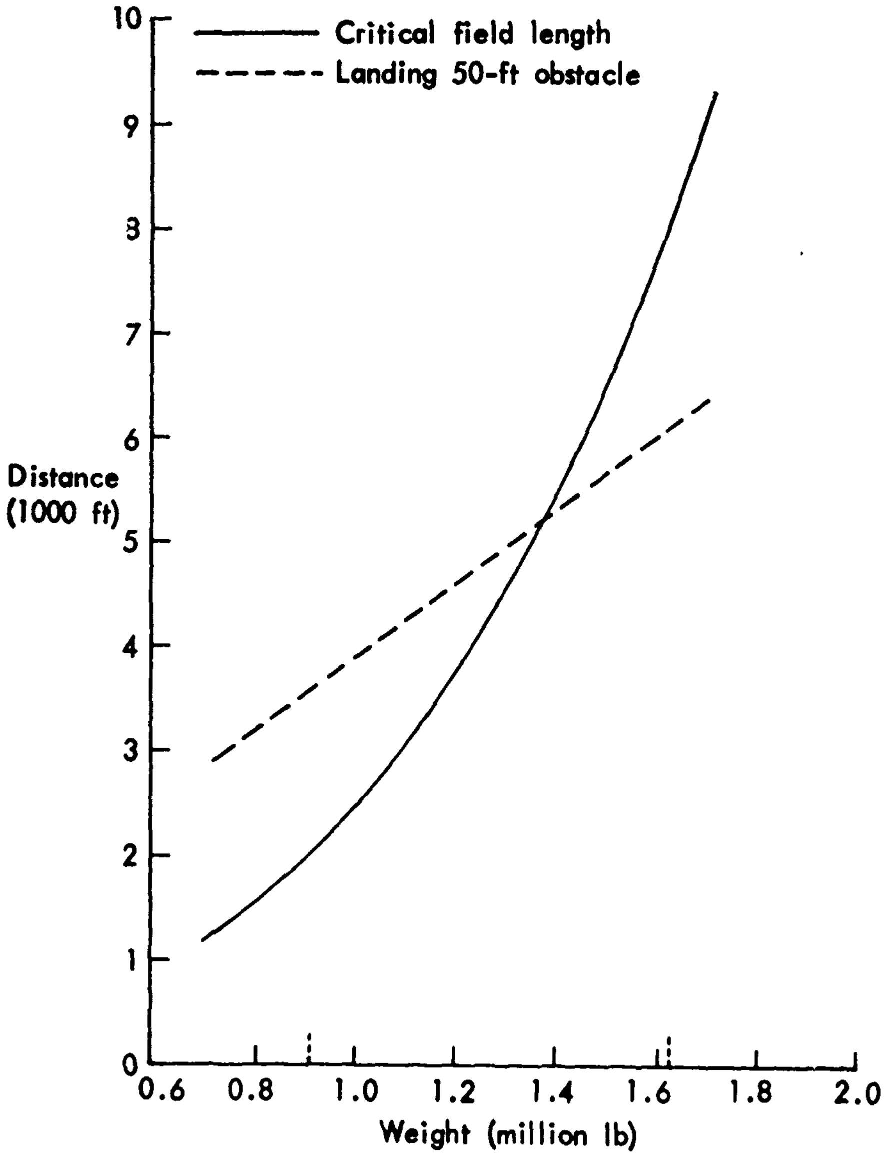

Fig. A-20—Field-length characteristics of the VLA-LH_2*

Design-Point Nuclear Aircraft (VLA-NUC)

Figures A-21 and A-22 show the general arrangement of the nuclear-powered aircraft. The flight envelope is depicted by Fig. A-23 and the field-length requirements are illustrated in Fig. A-24.

The design rules for this aircraft differed considerably from those of the other aircraft in the study. The cargo compartment was divided into two bays (one immediately ahead and one immediately aft of the reactor); this was to allow the reactor and containment vessel to be integrated into the wing-box structure. Another major difference in the configuration was the location of the engines; they are positioned on top of the fuselage above the reactor. Power is supplied to engines from the reactor via a liquid-metal heat-transfer system using vacuum insulated piping (see Appendix B). Since the liquid metal and piping system are extremely heavy, the engines were located as close as possible to the reactor to minimize weight and reduce the vibrational loads imposed on the long coolant lines.

For safety purposes, we have defined a different design mission profile for the nuclear aircraft in order to minimize nuclear reactor operation in low altitude flight. The aircraft was designed to take off on JP and, after reaching a safe altitude, convert to nuclear operation. Thirt ·inutes were allotted to bring the nuclear system up to power and make the transition from JP to full nuclear-powered flight. Similarly, reactor shutdown was begun 30 minutes prior to landing. The aircraft was also constrained to carry enough JP to provide for emergency recovery at any point in the mission; an 850 n mi range was thought to be sufficient for this purpose. The collective impact of these constraints made the nuclear-powered aircraft when designed to perform a radius mission weigh nearly one million pounds more than the VLA-JP aircraft. Furthermore, the VLA-NUC carried almost two-thirds the JP the VLA-JP did. Clearly, the general utility and attractiveness of the nuclear-powered aircraft was greatly influenced by these constraints; the necessity of such constraints should, therefore, be investigated in much greater detail than was possible in the present work.

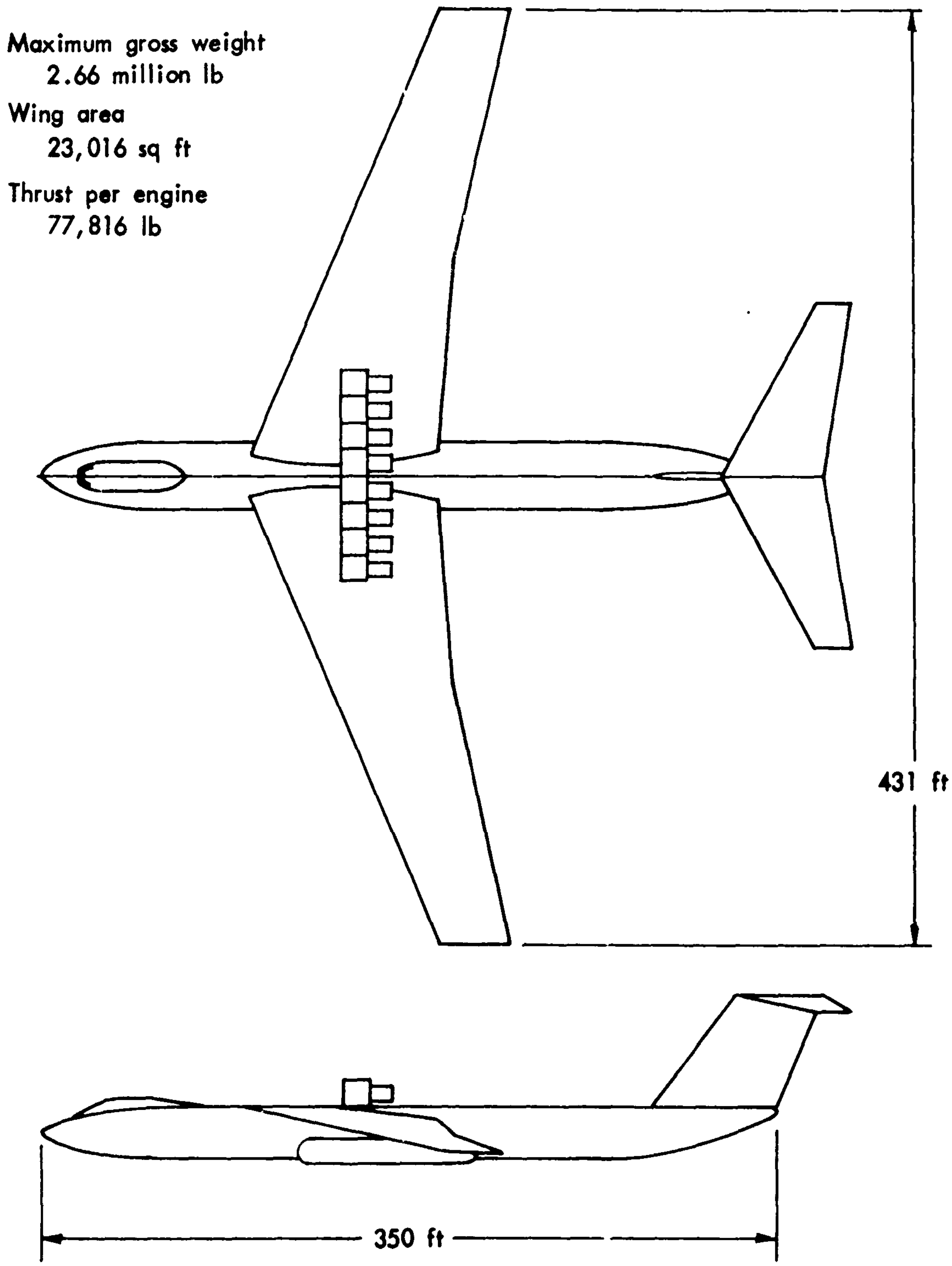

Fig. A-21 — General arrangement of the VLA-NUC

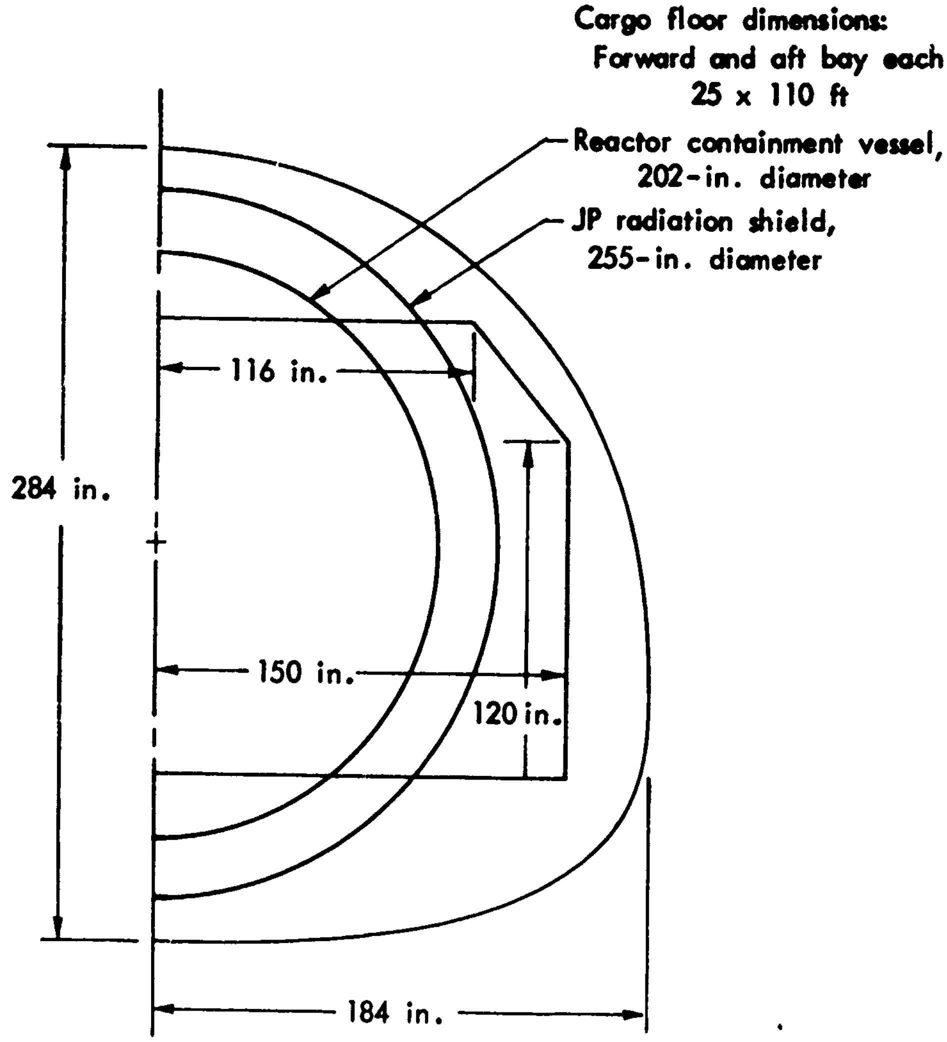

Fig. A-22—Fuselage cross section of the VLA-NUC

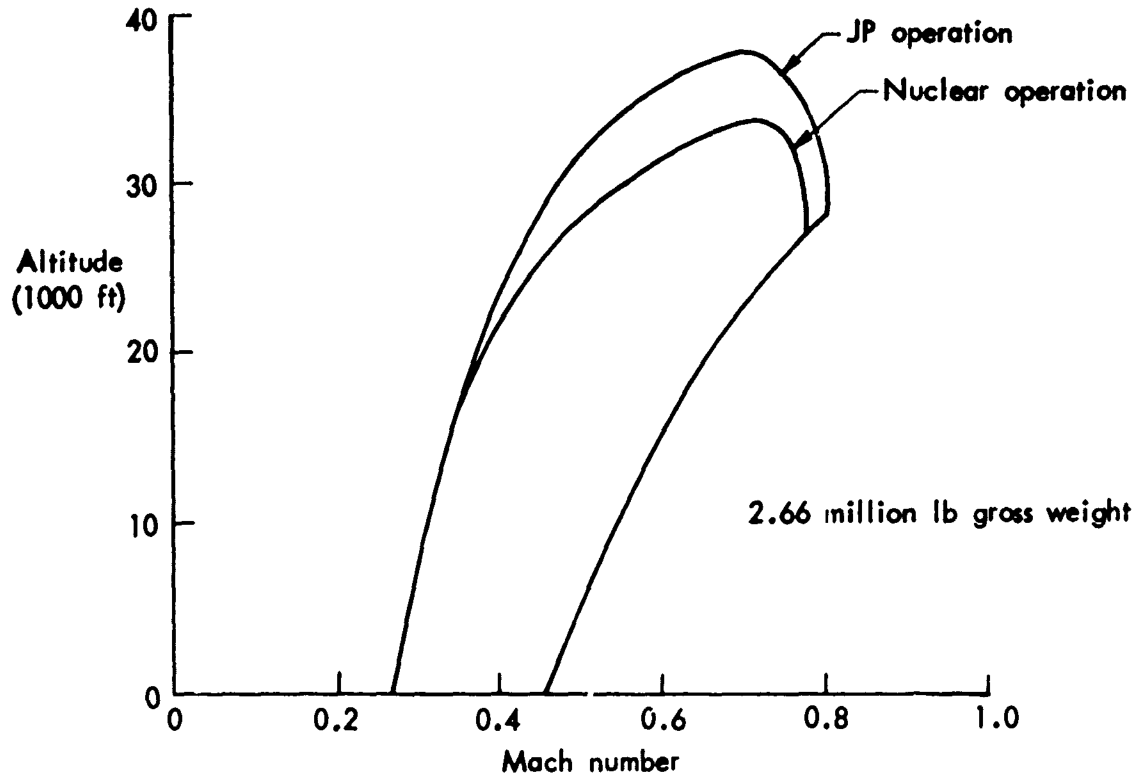

Fig. A-23—Flight envelope of the VLA-NUC

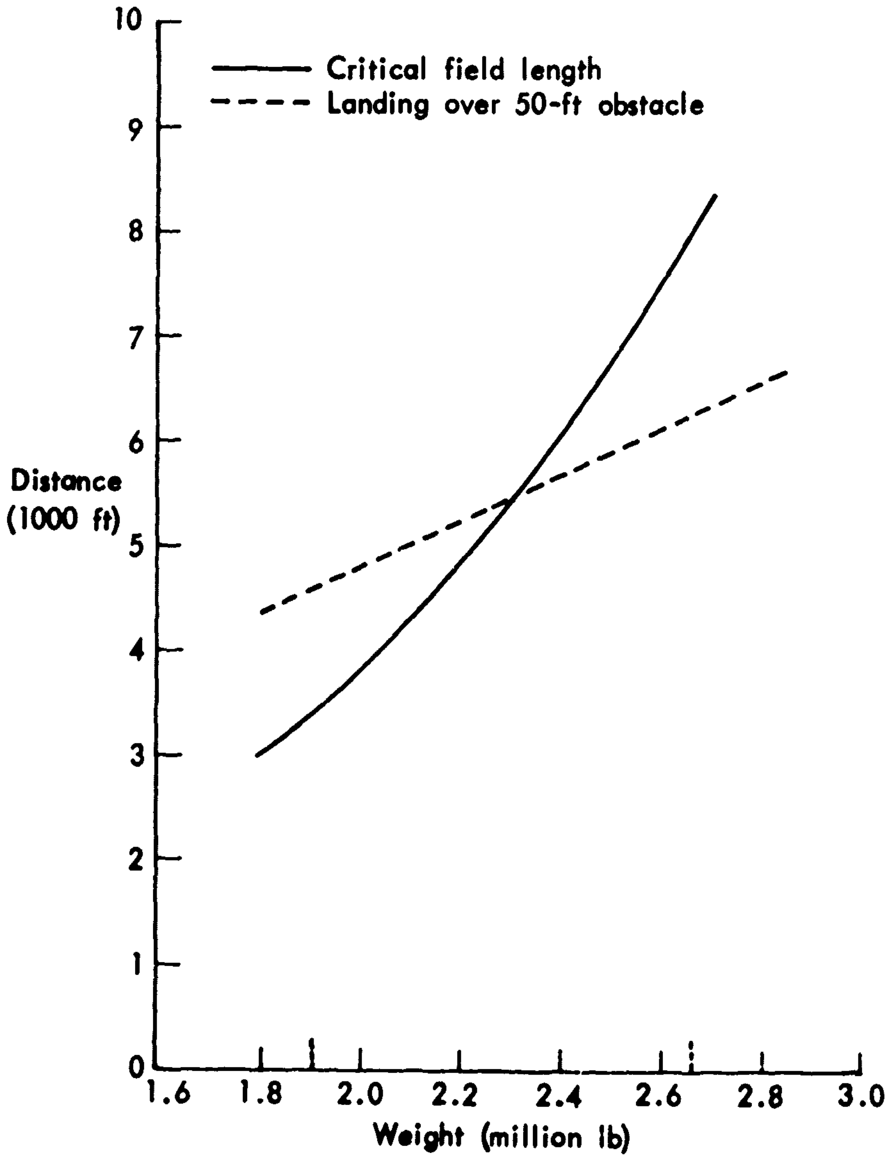

Fig. A-24—Field-length characteristics of the VLA-NUC

A summary of the mission segments for the VLA-NUC on the radius mission is:

1. After 5-minute warm-up, takeoff at normal rated power on JP fuel.
2. Climb to 30,000-ft altitude on JP fuel and begin reactor start-up.
3. Cruise for 20 minutes at 30,000-ft altitude on JP fuel while transitioning to full nuclear flight.
4. Cruise any desired distance on nuclear power. (Emergency fuel provided for 1250 n mi cruise at speed and altitude for maximum range.)
5. Cruise for 30 minutes at 30,000 ft on JP fuel during reactor shutdown.
6. Descend and land (no fuel allowance computed).
7. Off-load 350,000 lb of payload.
8. After 5-minute warm-up, takeoff at normal rated power on JP fuel.
9. Climb to 30,000-ft altitude on JP fuel and begin reactor start-up.
10. Cruise for 20 minutes on JP fuel while changing to full nuclear flight.
11. Cruise any desired distance on nuclear power. (Emergency fuel provided for 850 n mi cruise at speed and altitude for maximum range.)
12. Cruise for 30 minutes at 30,000 ft on JP fuel during reactor shutdown.
13. Descend and land (no fuel allowance computed).

This mission requires that a very large amount of JP be on-board the aircraft for emergency purposes only. To minimize the aircraft's gross weight, the emergency fuel was used to supplement the reactor shielding. Further remarks concerning the use of JP in reactor shielding are made in Appendix B.

Of course, the nuclear-powered airplane can carry a substantially larger payload on a range-mission profile. Trading the fuel weight required for the return leg permits the payload to be increased to 480,000 lb.

Excursion-Case Nuclear Aircraft (VLA-NUC*)

To provide some insight into the capability of a smaller nuclear-powered aircraft, an alternate design was developed. The design mission was the same as that for the baseline nuclear aircraft, except that the payload was reduced to 230,000 lb for the radius-mission profile; when flying range missions, the payload of the VLA-NUC* aircraft can be increased to 325,000 lb. The general arrangement for the VLA-NUC* aircraft is shown in Figs. A-25 and A-26. Note that the cargo floor length has been shortened to 62 ft for each cargo bay. This results in a cargo floor loading of 75 lb per square foot, which is modestly higher than 64 lb per square foot for the other designs in this study.

The resultant maximum gross weight for the VLA-NUC* aircraft is 1.94 million lb. Figure A-27 provides the operating flight envelope for this aircraft and Fig. A-28 its takeoff and landing characteristics.

To complete our description of the nuclear-powered airplanes, Table A-3 presents data on total JP consumption for selected situations.

AREAS REQUIRING FURTHER STUDY

In addition to the concern over the weight prediction techniques used in the present effort, there are some other areas which warrant further study.

The design and placement of the landing gear is an especially difficult problem for very large aircraft. It has implications on the numbers and types of runways that can be sued by these aircraft and directly affects their ground maneuvering capabilities. For this study, it was assumed that a satisfactory fuselage-mounted gear arrangement could be achieved. The gear weight was estimated on the basis of statistical trends of gear weight versus maximum takeoff weight.

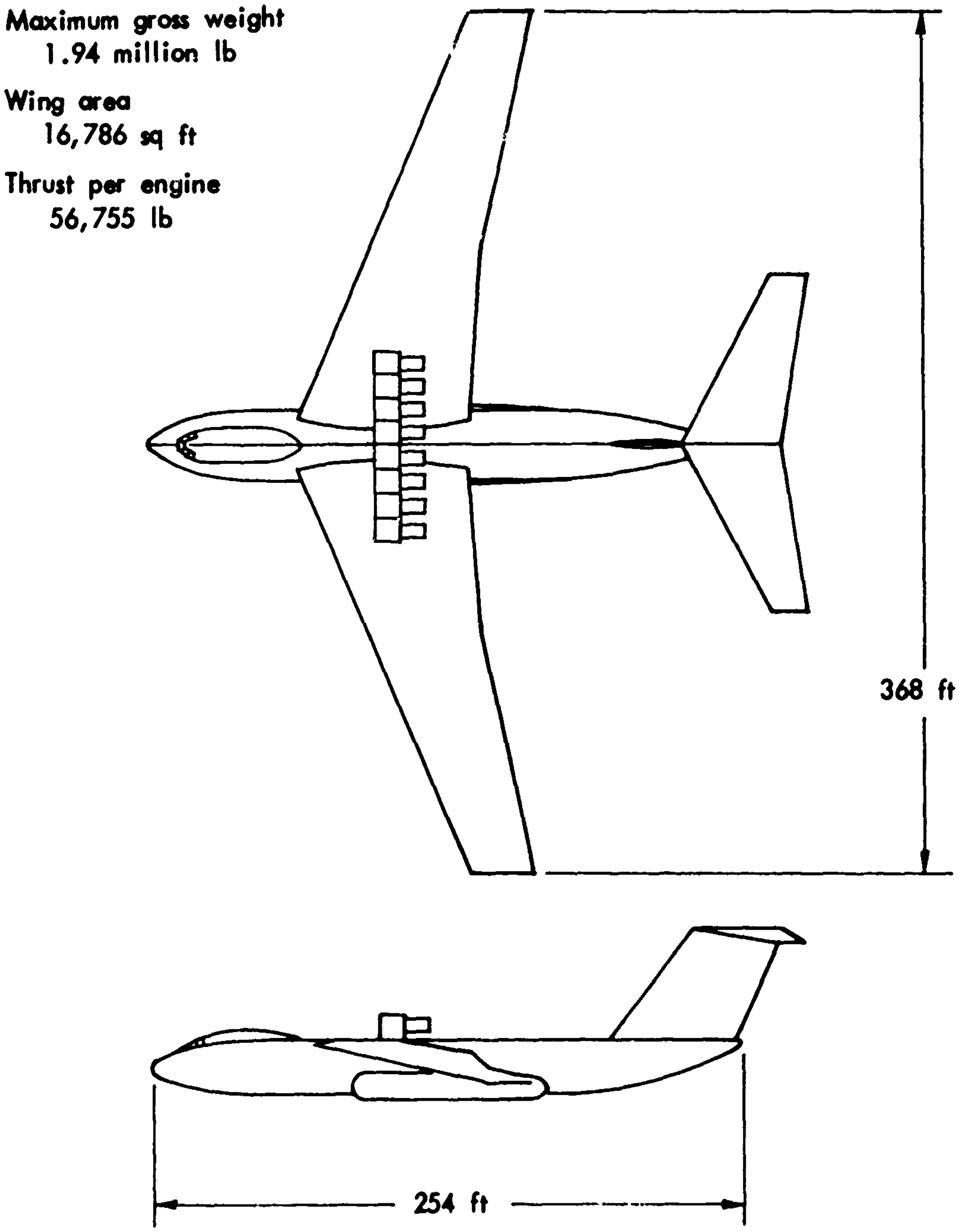

Fig. A-25—General arrangement of the VLA-NUC*

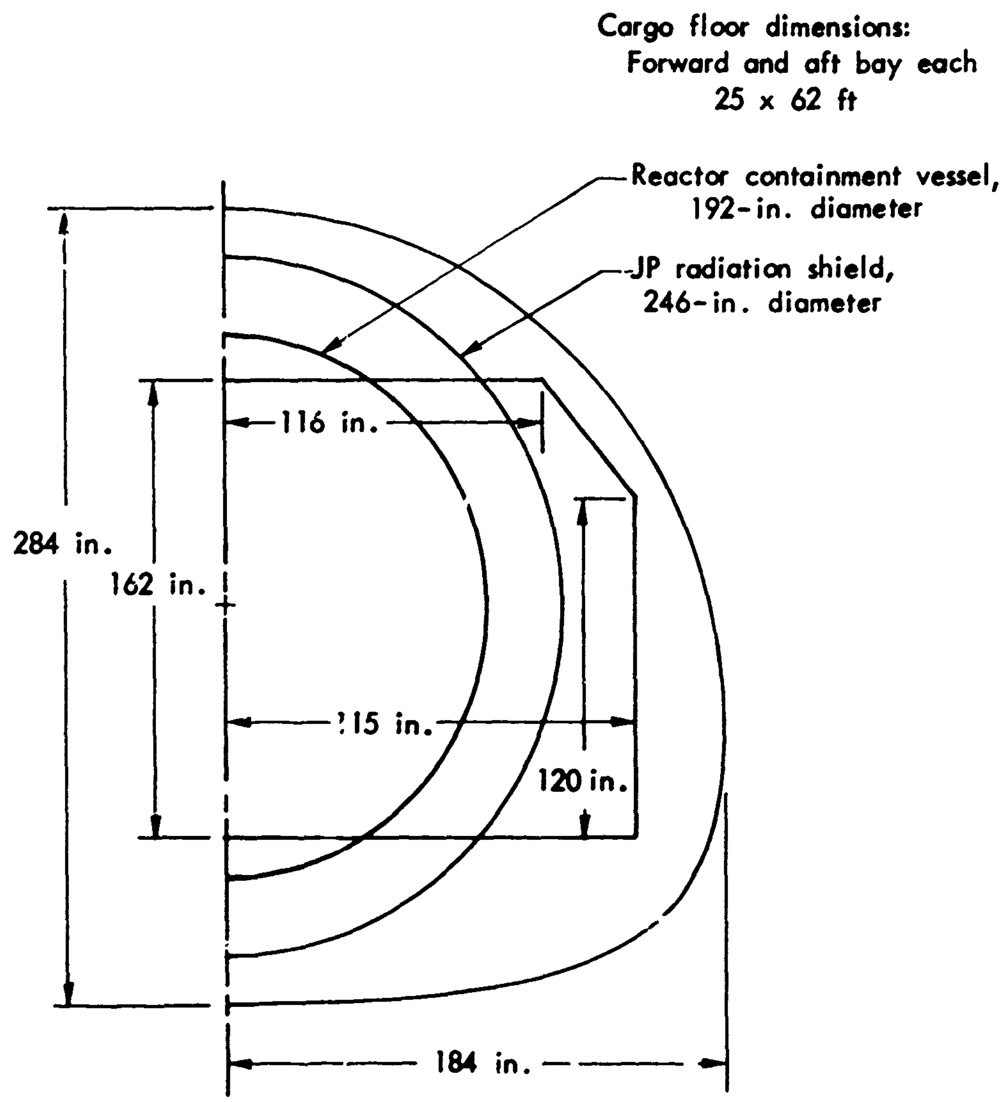

Fig. A-26—Fuselage cross section of the VLA-NUC*

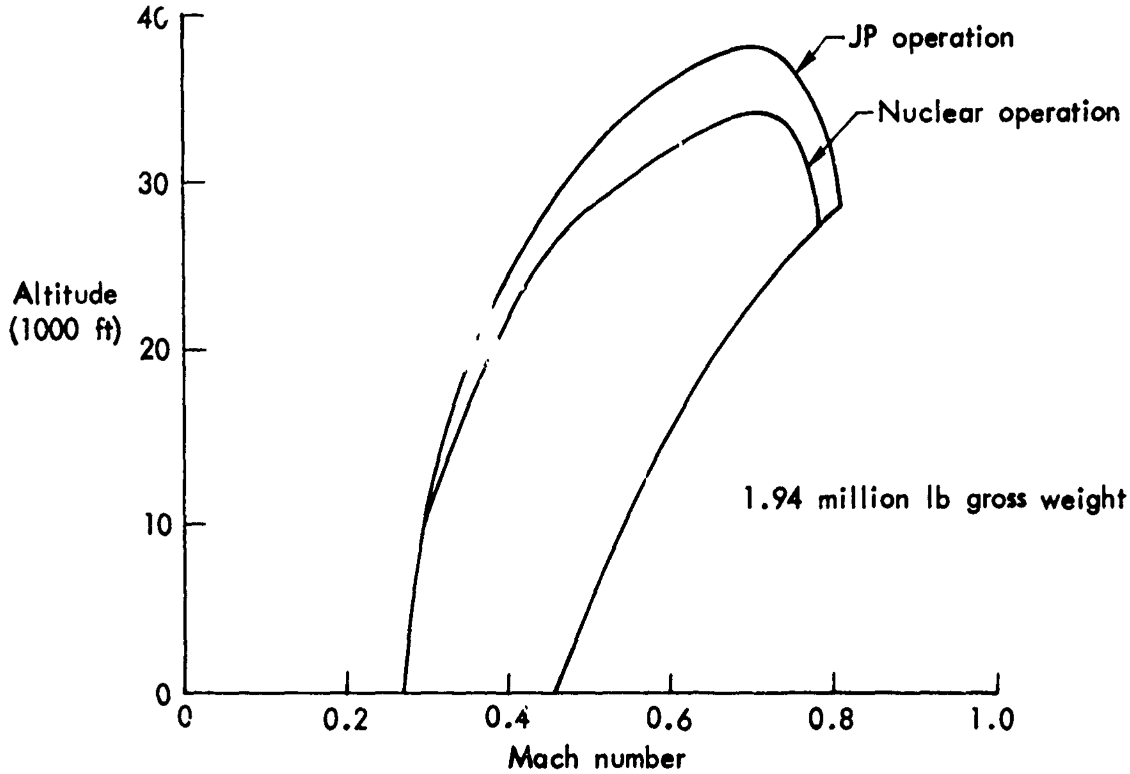

Fig. A-27—Flight envelope of the VLA-NUC*

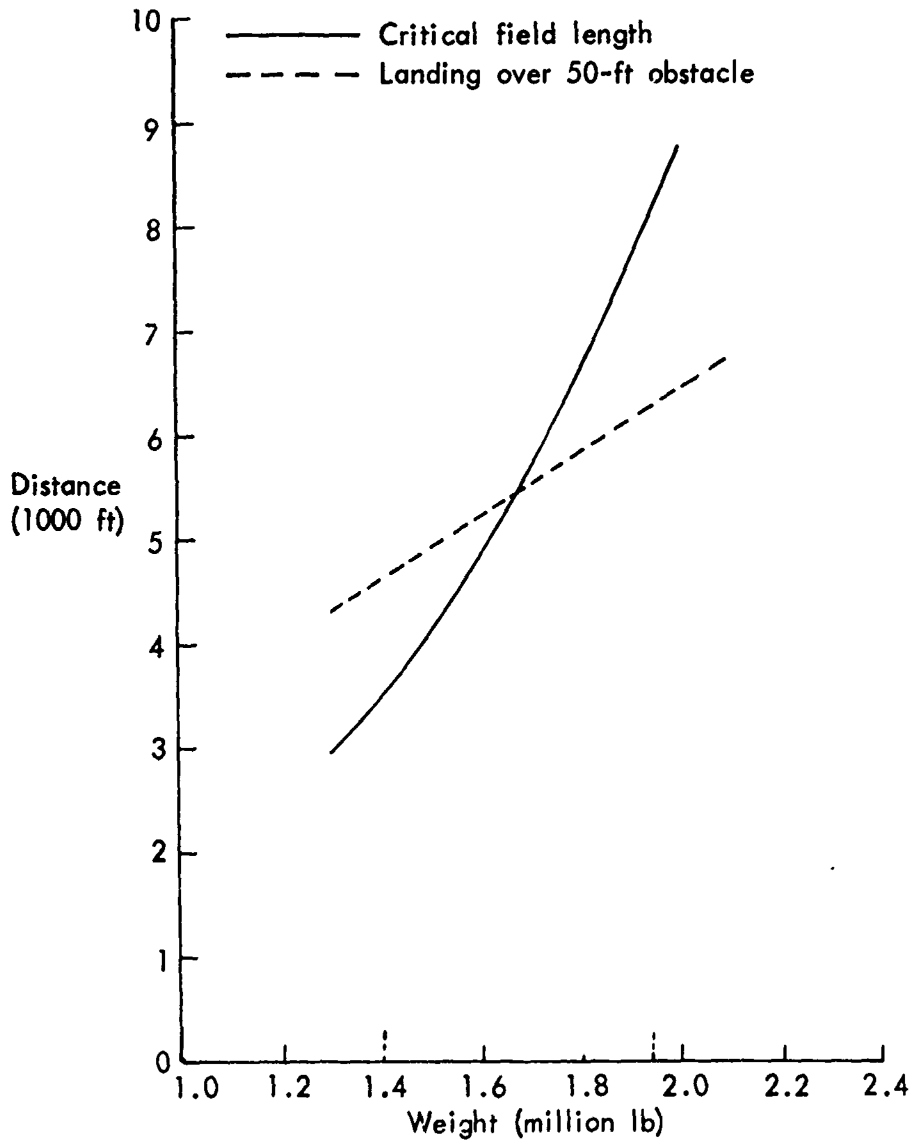

Fig. A-28—Field-length characteristics of the VLA-NUC*

Table A-3

TOTAL JP CONSUMPTION BY NUCLEAR AIRPLANES DURING DESIGN MISSIONS AND SELECTED FLIGHT SEGMENTS (lb)

Mission or Segment	VLA-NUC	VLA-NUC*
Radius mission	276,244	203,395
Range mission	143,066	105,388
Warmup, takeoff, and climb[a]	64,467	48,108
Cruise for 50 minutes[b]	78,598	57,279

[a]At maximum gross takeoff weight.

[b]With maximum payload.

The high-lift flap system is another area that warrants additional study. Since their fuselage lengths prevent these aircraft from rotating to high angles of attack during takeoff and landing, the high-lift system must be designed to produce a takeoff lift coefficient on the order of 1.6. With the current state of the art, this would require a triple-slotted trailing-edge flap over 75 percent of the wing span and a leading edge flap out to 95 percent span. Also, to obtain a lift coefficient of 1.6 would require a very high fowler motion with a deflection of 30 degrees.

Appendix B

PROPULSION SYSTEM DESIGN ANALYSIS

The installed engine performance data presented in this appendix were generated by the Propulsion Division, Deputy for Development Planning, Aeronautical Systems Division, and are based upon projections of future large turbofan engines that incorporate modestly advanced technology.

Conventional turbofan systems using JP, hydrogen, or methane were considered as well as a dual-mode turbofan system capable of operating on nuclear-supplied heat or JP. Complete installed performance, dimensional, and weight data were generated for a conventional JP-fueled engine and a dual-mode (nuclear/JP) system. Appropriate factors were developed and applied to the JP-engine installed performance data to obtain corresponding data for the hydrogen and methane-fueled systems.

CONVENTIONAL TURBOFANS (CHEMICAL FUELS)

The engines for each of the chemical-fueled airplanes are high-bypass-ratio, high-pressure-ratio turbofans having turbine inlet temperatures moderately higher than those of presently available engines. These engines represent a technology level well within that forecast for the early 1980s. Table B-1 presents propulsion system characteristics for the alternatively fueled airplanes. These data are for the thrust-size that the aircraft design analysis determined to be the optimum for each aircraft configuration. The JP-fueled system served as the baseline engine.

Baseline Engine (VLA-JP)

Installed performance data for the baseline propulsion system were generated using the "Simulation of Turbofan Engines" (SMOTE) computer program developed by the Air Force Aero Propulsion Laboratory. Techniques developed at ASD were employed to correct for the appropriate external drags. Installation factors used to estimate these losses are listed in Table B-2. The external drags include fan-cowl friction drag, fan-nozzle boattail pressure drag, and scrub drag on the appropriate surfaces.

Table B-1

PROPULSION SYSTEM CHARACTERISTICS: CONVENTIONAL TURBOFAN ENGINES

Characteristic	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-LH_2*
Number of engines	6	6	6	6
Performance at maximum sea level static power				
- Installed thrust (lb)	81,570	83,420	56,400	71,740
- Installed TSFC (lb/hr/lb)	0.296	0.257	0.109	0.109
Performance at maximum continuous power (M = 0.8, 30,000 ft)				
- Installed TSFC (lb/hr/lb)	0.624	0.542	0.230	0.230
Bypass ratio	10	10	10	10
Fan pressure ratio	35	35	35	35
Maximum turbine inlet temperature (°F)	2,500	2,500	2,500	2,500
Maximum dynamic pressure (lb/ft^2)	630	630	630	630
Maximum Mach number	1.0	1.0	1.0	1.0
Engine length (in.) (fan to nozzle exit)	239.9	241.8	210.9	229.4
Engine maximum diameter (in.)	131.0	132.4	108.9	122.8
Engine weight (lb)	12,199	12,546	7,690	10,390
Thrust reverser weight (lb)	2,074	2,133	1,307	1,766

Table B-2

FACTORS USED IN CALCULATING INSTALLATION LOSSES FOR THE BASELINE JP ENGINE (VLA-JP)

Factor	Assumed Value
Inlet pressure recovery (M = 0)	0.970
Inlet pressure recovery (M = 0.2)	0.995
Compressor air bleed (lb/sec/engine)	3.0
Horsepower extraction (hp/engine)	307
Nozzle gross thrust coefficient	0.99

NOTE: The values of compressor air bleed and horsepower extraction are assumed to vary with aircraft size, hence with engine size.

A fan-stream-only cascade-type thrust reverser with the following characteristics was assumed.

$$W_{tr} = 0.17W_{be} \tag{B-1}$$

and

$$T_R = 0.5G_{fan} + R_{fan} - N_{core} \tag{B-2}$$

where

W_{tr} - thrust reverser weight
T_R - magnitude of reverse thrust
W_{be} - bare engine weight
G_{fan} - gross thrust of fan stream
R_{fan} - ram drag of fan stream
N_{core} - net thrust of core stream

Installed propulsion system performance, weight, and dimensional data were generated for a given thrust-size engine. The following equation and scaling factors were used to obtain weight and dimensional data for the variations in engine thrust that are required for the specific designs that the aircraft design analysis developed (see Appendix A).

$$\frac{\text{Scaled Parameter}}{\text{Baseline Parameter}} = \left(\frac{\text{Scaled Thrust}}{\text{Baseline Thrust}}\right)^n \qquad \text{B-3}$$

where

$n = 1.25$ for engine weight

$n = 0.35$ for engine length

$n = 0.50$ for engine diameter

Installed propulsion-system performance data for the JP-fueled engine at various operating conditions are presented in Figs. B-1 through B-5. (Note that "intermediate power" corresponds to the maximum power available for climbout, etc.) Figure B-6 is a sketch of the engine nacelle for the VLA-JP.

Other Chemical-Fueled Engines

Engines using either hydrogen or methane were assumed to be of the same general design as the JP-fueled engine and no changes in weight or external dimensions were made for a given thrust size. We assumed that the installed-thrust specific fuel consumption of the resized engine when operating on a fuel other than JP was wholly accounted for by the change in the gravimetric heat of combustion of the new fuel compared to JP (see Section III). The thrust specific fuel consumption for the methane- and hydrogen-fueled engines were thus obtained by multiplying the specific fuel consumption of the resized JP-fueled engine by 0.869 and 0.370, respectively.

Variations in total thrust and thrust per pound of airflow due to the use of the different fuels were considered to be negligible. However, some of the factors used to calculate installation losses were assumed to be different from that shown in Table B-2; these changes are shown in Table B-3 (p. 208).

NUCLEAR-PROPULSION SYSTEMS

Public safety considerations dictate that the overriding design goal of a nuclear-propulsion system must be to prevent the release of radioactive materials under all conditions. This goal must be pursued

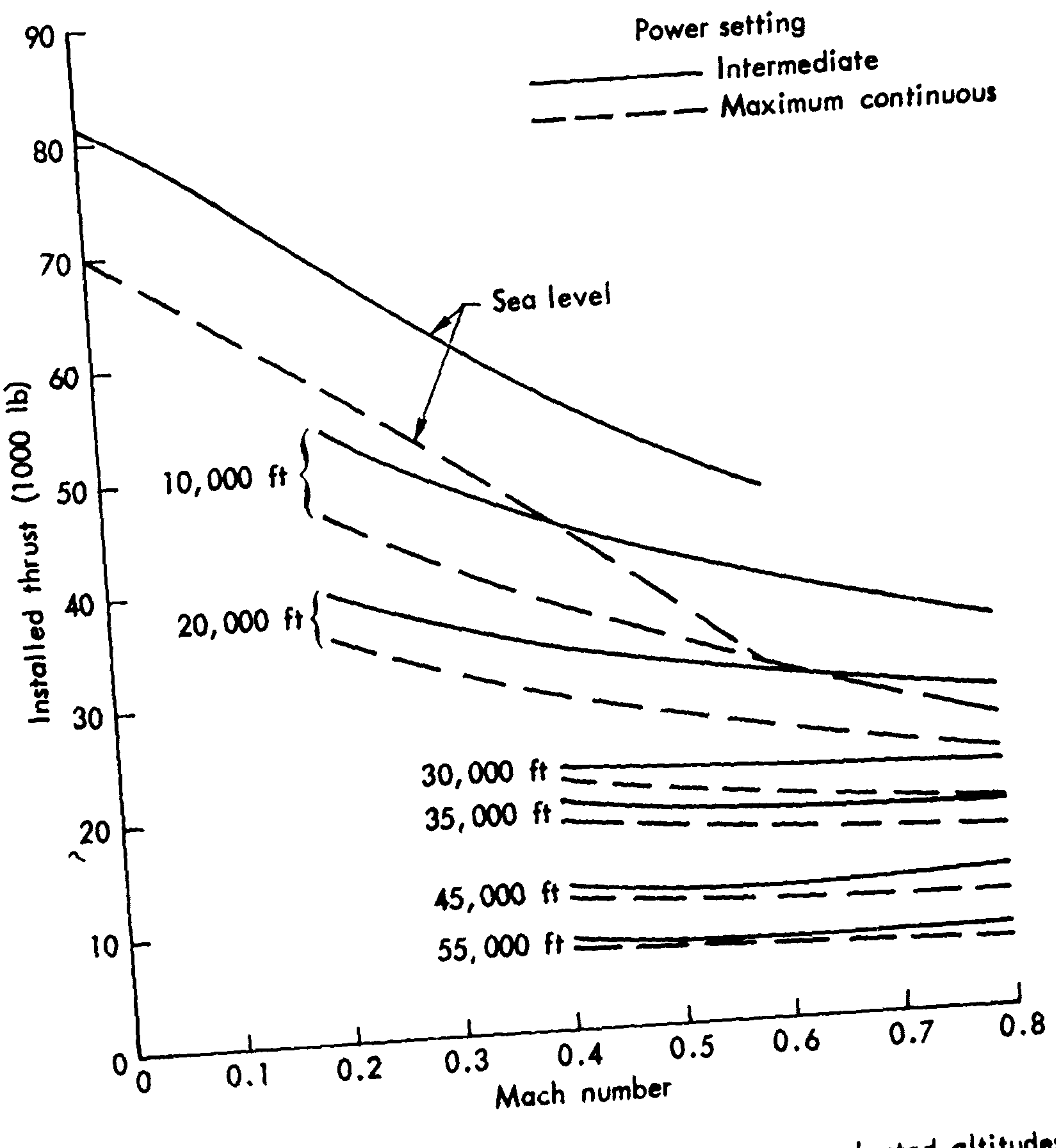

Fig. B-1 — Installed thrust of the VLA-JP engine at selected altitudes

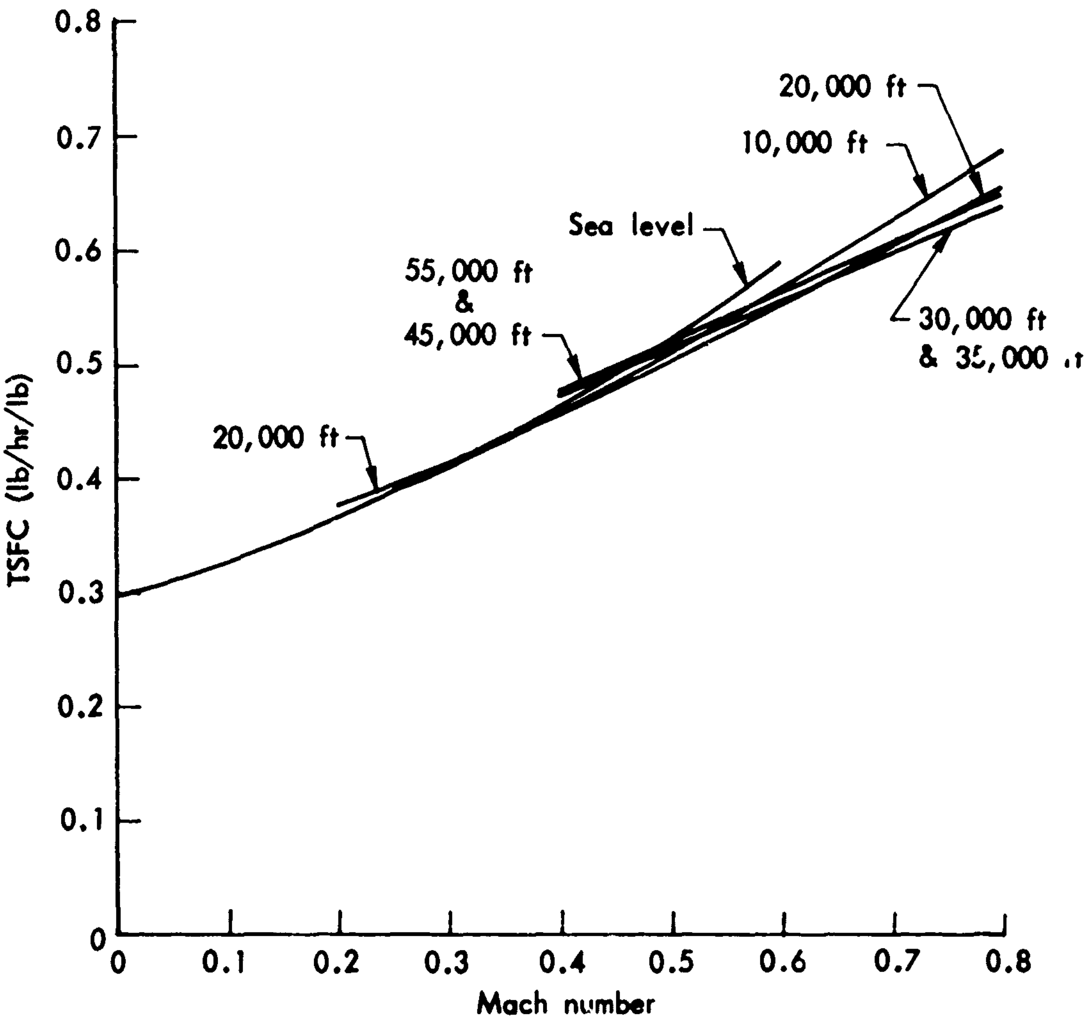

Fig. B-2—Installed thrust-specific fuel consumption of the VLA-JP engine at intermediate power

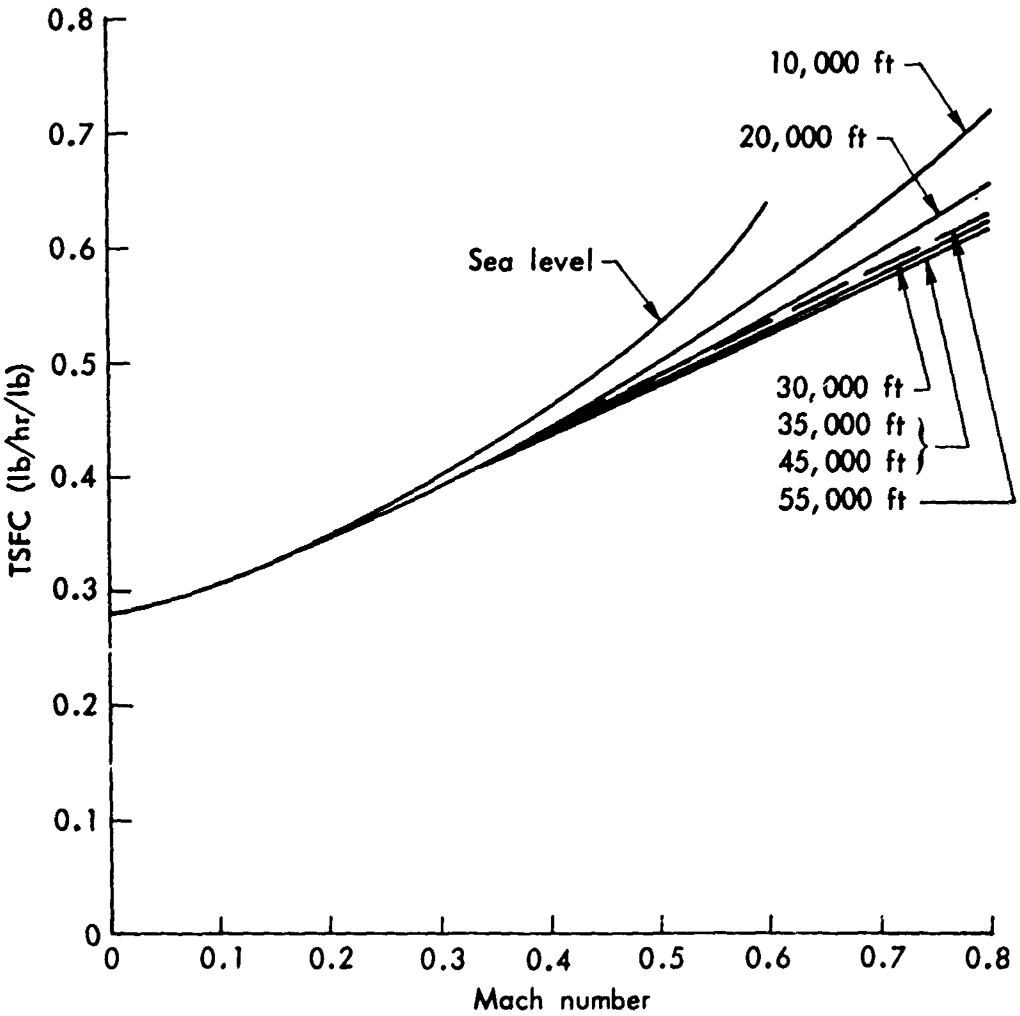

Fig. B-3 — Installed thrust-specific fuel consumption of the VLA-JP engine at maximum continuous power

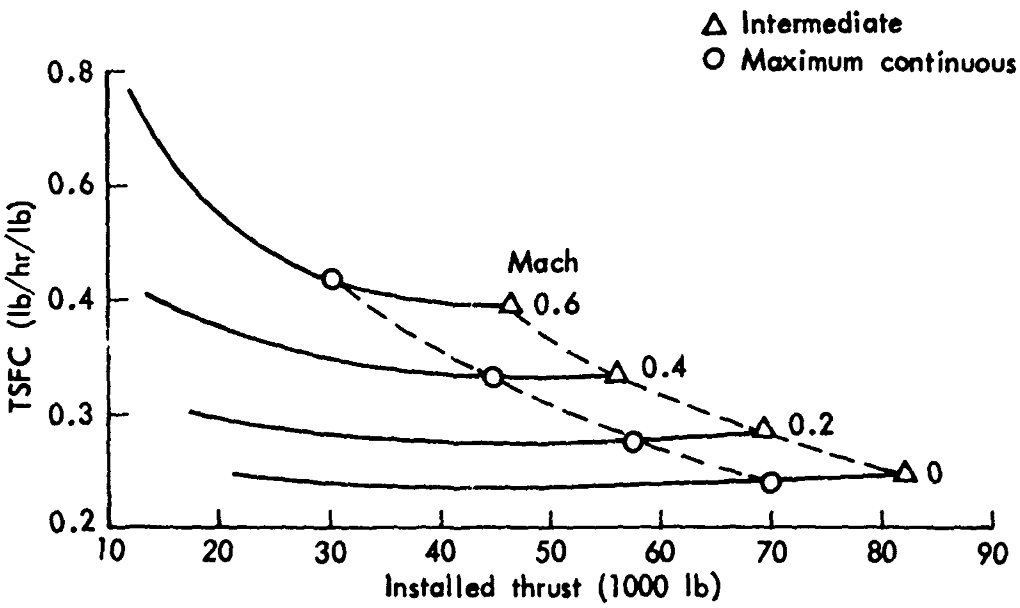

Fig. B-4a — Installed performance of the VLA-JP engine at sea level

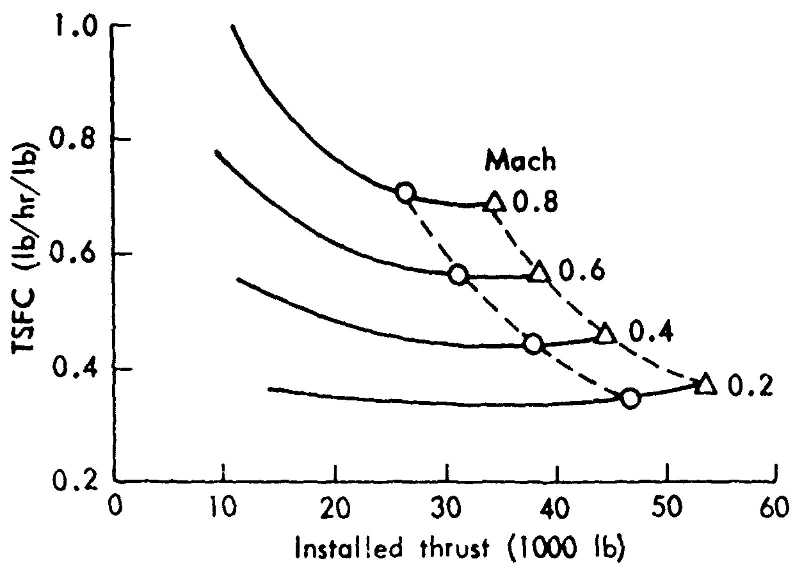

Fig. B-4b — Installed performance of the VLA-JP engine at 10,000 ft

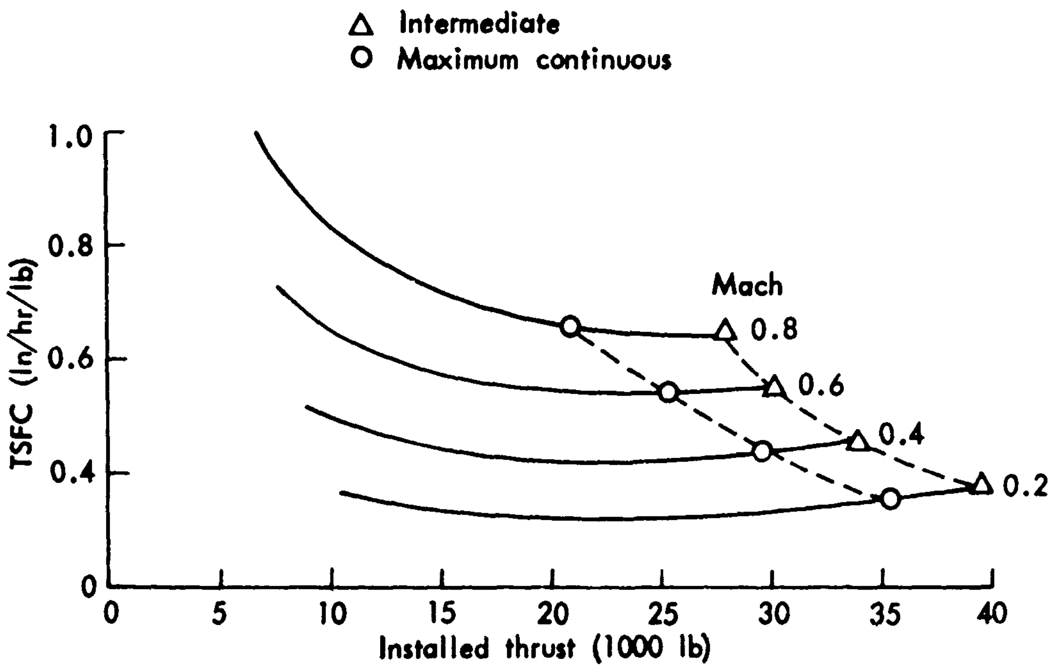

Fig. B-4c—Installed performance of the VLA-JP engine at 20,000 ft

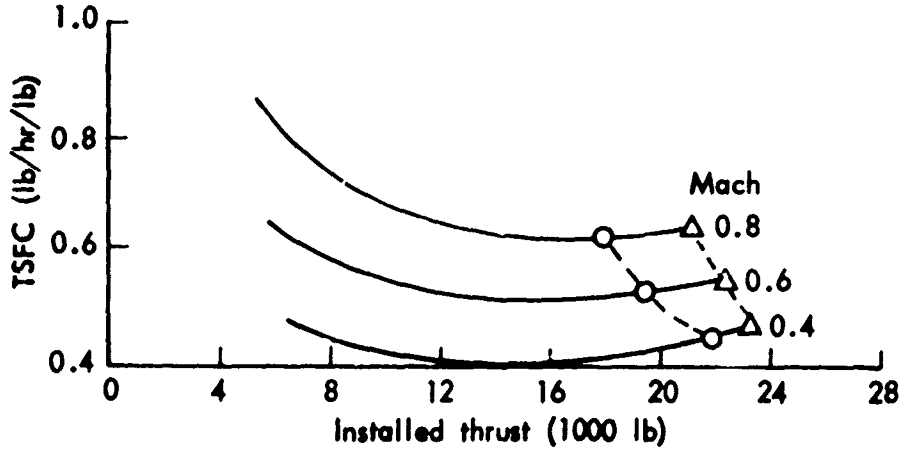

Fig. B-4d—Installed performance of the VLA-JP engine at 30,000 ft

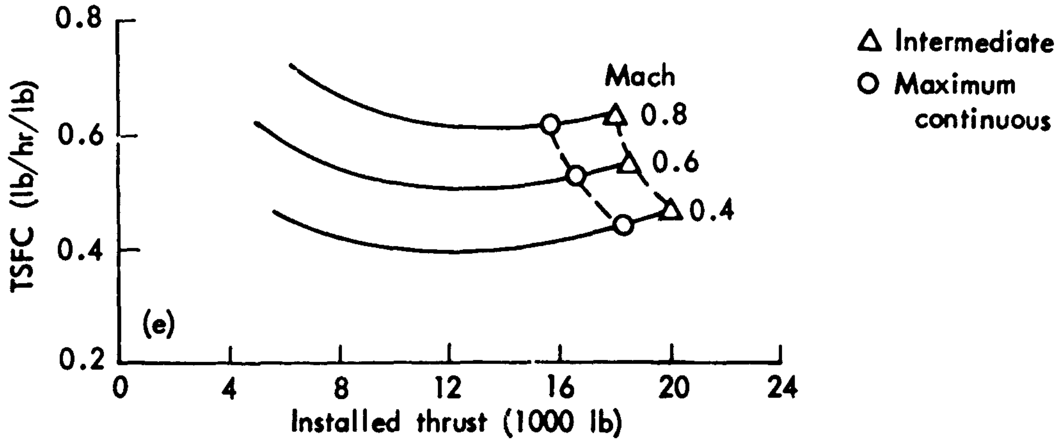

Fig. B-4e—Installed performance of the VLA-JP engine at 35,000 ft

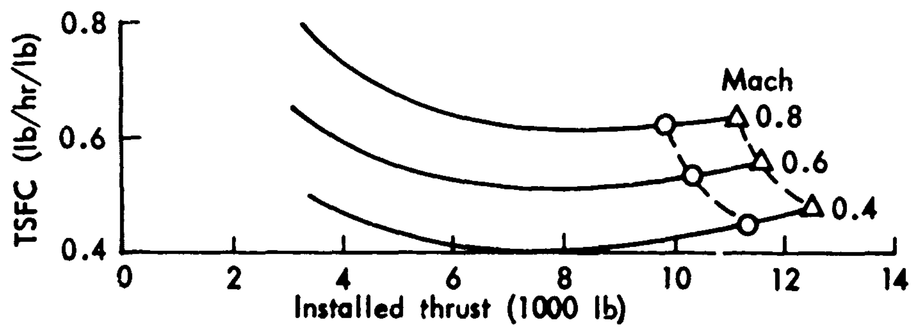

Fig. B-4f—Installed performance of the VLA-JP engine at 45,000 ft

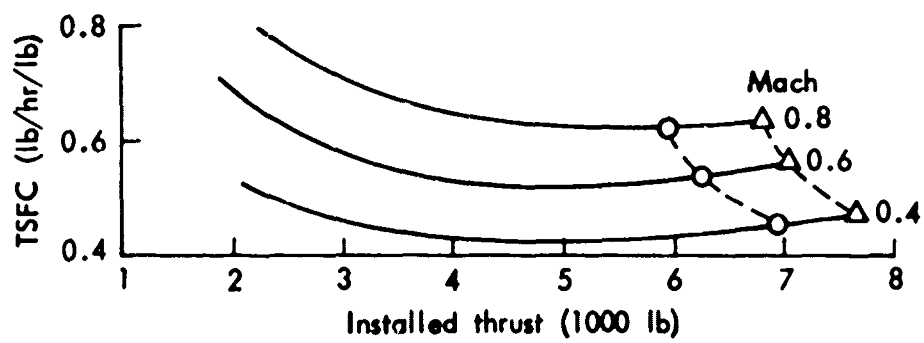

Fig. B-4g—Installed performance of the VLA-JP engine at 55,000 ft

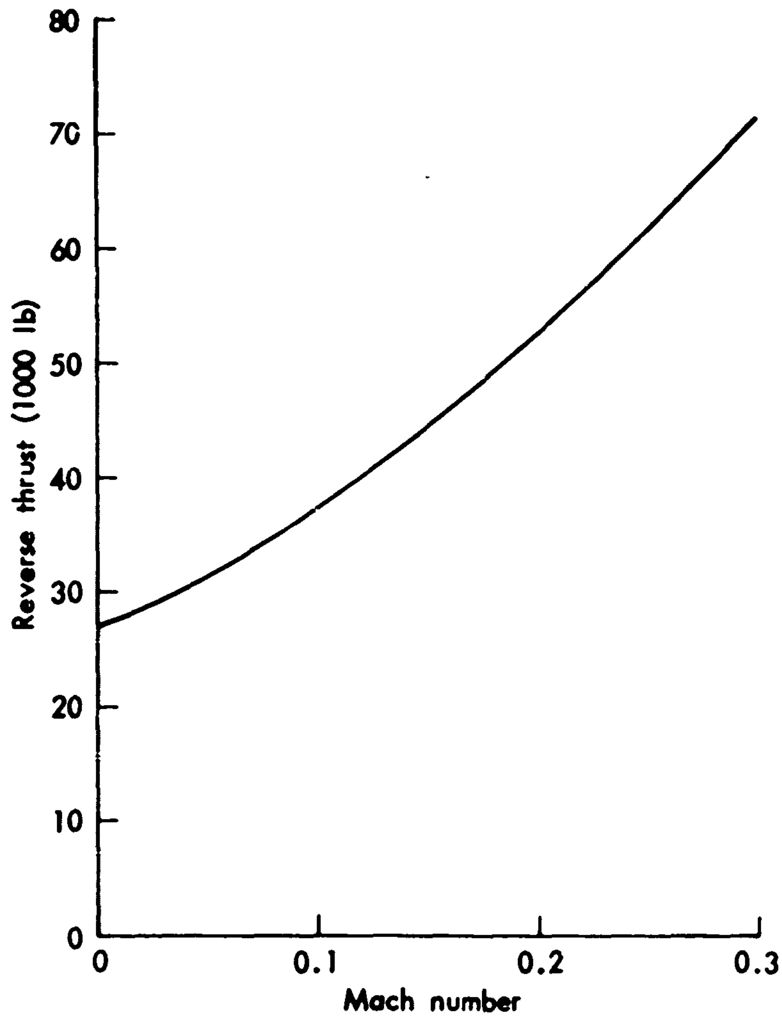

Fig. B-5 — Reverse thrust of the VLA-JP engine at sea level

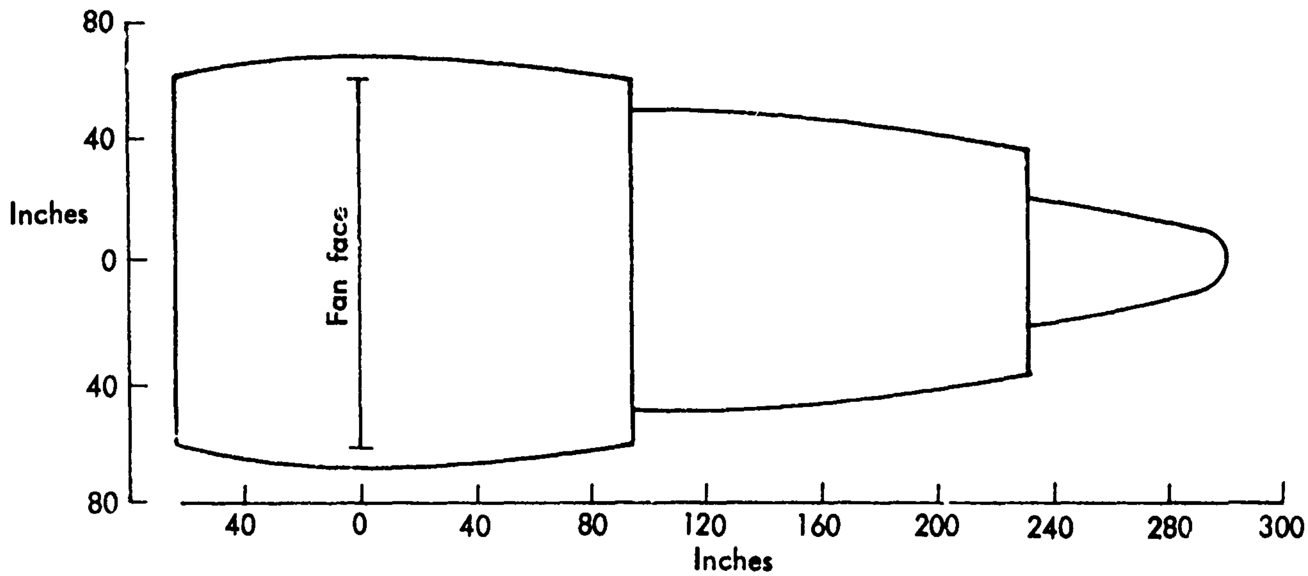

Fig. B-6—VLA-JP engine nacelle

Table P-3

MODIFIED FACTORS USED IN CALCULATING INSTALLATION LOSSES FOR THE CRYOGENIC-FUELED AIRPLANES

Factor	Assumed Value		
	VLA-LCH_4	VLA-LH_2	VLA-LH_2*
Compressor air bleed (lb/sec/engine)	3.1	2.1	2.7
Horsepower extraction (hp/engine)	314	212	270

NOTE: Other factors are identical to the JP-fueled engine.

within the constraint of achieving a useful military system at minimum weight. The simple "brute force" approach of packaging the nuclear system so that it can withstand every conceivable accident is not possible within the bounds of reasonable propulsion system weights. Nor does this approach appear necessary, since a combination of operational constraints and safety design features can achieve the same ends.

In this study, we have chosen to exploit a combination approach that places certain restrictions upon the flight profile of the aircraft during reactor operation and provides enough protection to enable the nuclear system to survive all but the most severe crash conditions. The restrictions upon the aircraft flight profile are discussed in Appendix A. The design of the reactor safety features are considered here.

A closed two-loop coolant system was selected in order to isolate all the components having the potential for direct contact with fission products (i.e., reactor, shield, primary coolant lines, and primary heat exchangers). The entire primary heat transfer loop is enclosed within a spherical, heavy-metal containment vessel designed to withstand an impact of 300 feet per second (fps) against a solid object.

A value of 300 fps was chosen because it is representative of typical aircraft takeoff and landing speeds; most aircraft accidents, at least in the transport category, occur during takeoff or landing [10]. Thus, by avoiding reactor operation near populated areas and

by designing the nuclear system to survive a 300 fps impact, we were able to reduce the safety risk to the general public significantly.

During the initial aircraft sizing exercises, no attempt was made to utilize the emergency JP fuel as auxiliary neutron shielding and the resultant aircraft design weights were in excess of 3 million lb (TOGW). Since this design approach did not represent the best design practice for achieving minimum weight systems and since it imposed excessive weight penalties on the aircraft, it was not pursued in subsequent activity to refine the aircraft designs.[a]

The nuclear-propulsion system consists of a liquid-metal-cooled reactor, an indirect heat transfer system, and eight turbofan engines of medium bypass ratio. The engines are capable of dual-mode operation (i.e., they can operate in either the nuclear-reactor heating mode or the conventional chemical-fueled mode using JP). The systems for the two aircraft configurations vary in total thrust output and hence in the physical size of the various components. A generic description of the complete system is shown schematically in Fig. B-7.

We first discuss the design characteristics of the dual-mode turbofan engines and follow with a similar description of the nuclear system (reactor plus heat exchangers).

Dual-Mode Turbofan Engine

The dual-mode turbofan engine was developed by the United Aircraft Research Laboratories (UARL) in a previous study [76]. Installed propulsion-system performance data were generated using a UARL computer model [77] supplemented by ASD-developed techniques. The latter were used to correct the data for appropriate external drags and to generate performance data which were outside the nuclear-mode operating envelope of the UARL computer program. These performance data, and also the dimensional and weight data, were generated for a fixed total

---

[a]Later studies have indicated that the requirement that nuclear airplanes take off and land on JP fuel alone may not be necessary, since the safety risk to the general public does not appear to change greatly for a nuclear-powered takeoff with chemical assist. If so, a significant further reduction in TOGWs for nuclear-powered aircraft would be possible.

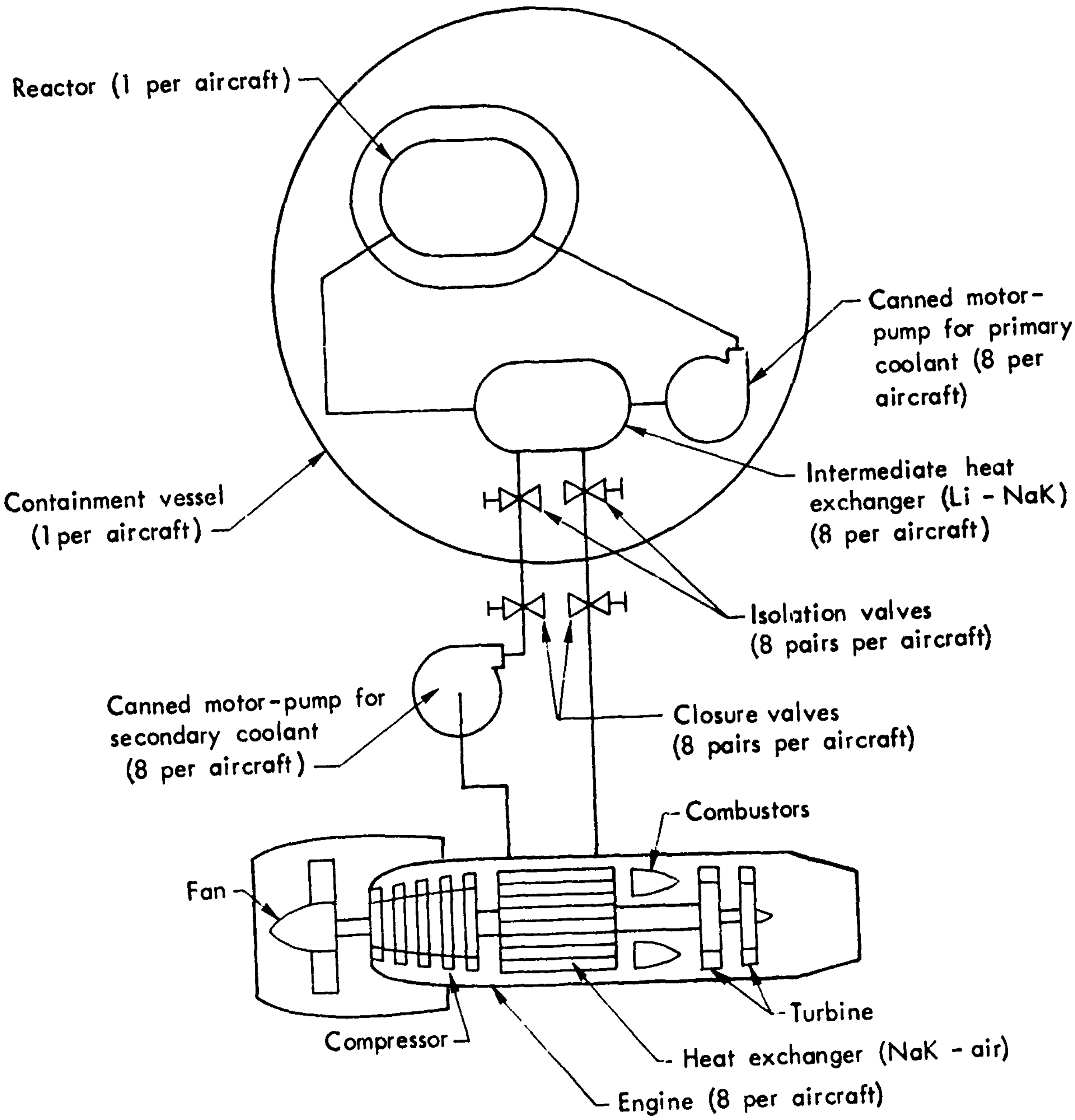

Fig. B-7—Schematic of the nuclear-propulsion system

thrust requirement and a fixed number of turbofan engines. The following exponents were used in the scaling equation (Equation B-3) to obtain dimensional and weight data for variations in engine-thrust size required for specific aircraft designs as determined by the aircraft design analysis.

$n = 1.17$ for engine weight
$n = 0.4$ for engine length
$n = 0.50$ for engine diameter

Installation factors used in the generation of performance data are presented in Table B-4. Table B-5 presents the characteristics

Table B-4

FACTORS USED IN CALCULATING INSTALLATION LOSSES FOR THE DUAL-MODE ENGINES

Factor	Assumed Value VLA-NUC	VLA-NUC*
Inlet pressure recovery (M = 0)	0.97	0.97
Inlet pressure recovery (M = 0.2)	0.995	0.995
Compressor air bleed (lb/sec/engine)	2.9	2.1
Horsepower extraction (hp/engine)		
- JP mode	338	297
- nuclear mode	1173	856
Nozzle gross thrust coefficient	0.99	0.99

of the dual-mode engine at the optimum thrust level for each aircraft, a level determined by the aircraft design analysis. The relatively low turbine inlet temperature is dictated by the temperature capability of the heat exchanger within the engine. Figure B-8 is a

Table B-5

CHARACTERISTICS OF THE DUAL-MODE TURBOFAN ENGINES

Parameter	VLA-NUC	VLA-NUC*
Number of engines	8	8
Performance at maximum sea-level static power		
- Installed thrust (lb)	77,818	56,755
- Installed TSFC (lb/hr/lb)	0.390	0.390
Bypass ratio	3.853	3.853
Fan pressure ratio	1.642	1.642
Overall pressure ratio	19.52	19.52
Maximum turbine inlet temperature (°F)		
- JP mode	1,874	1,874
- nuclear mode	1,600	1,600
Maximum dynamic pressure (lb/ft^2)	630	630
Maximum Mach number	1.0	1.0
Engine length (in.) (fan to nozzle exit)	227.6	200.6
Engine maximum diameter (in.)	121.1	103.4
Engine weight[a] (lb)	16,438	11,362
Thrust reverser weight (lb)	2,794	1,932

[a]Does not include radiator and coolant weight. (For radiator weight, see Table B-8.)

sketch of the engine nacelle for the VLA-NUC aircraft. Installed-propulsion-system performance data for the engine operating in the chemical mode (JP fuel) for various operating conditions are presented in Figs. B-9 through B-13. Installed performance data for operation in the nuclear mode are shown in Fig. B-14. These performance data are for the engines used in the VLA-NUC aircraft configuration.

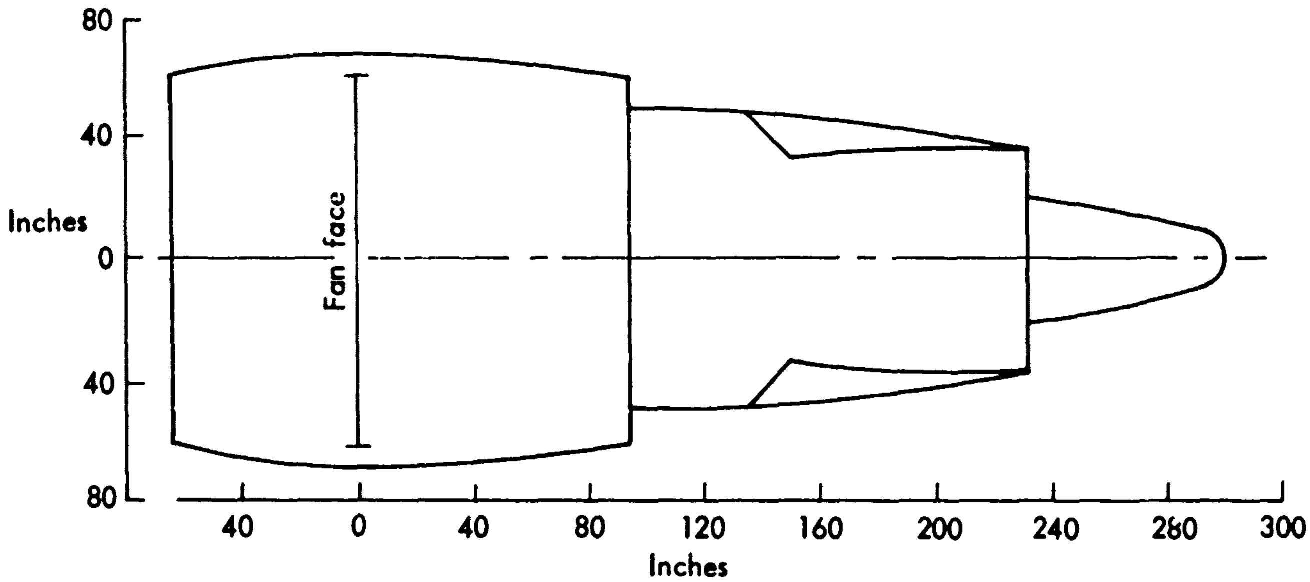

Fig. B-8—VLA-NUC dual-mode engine nacelle

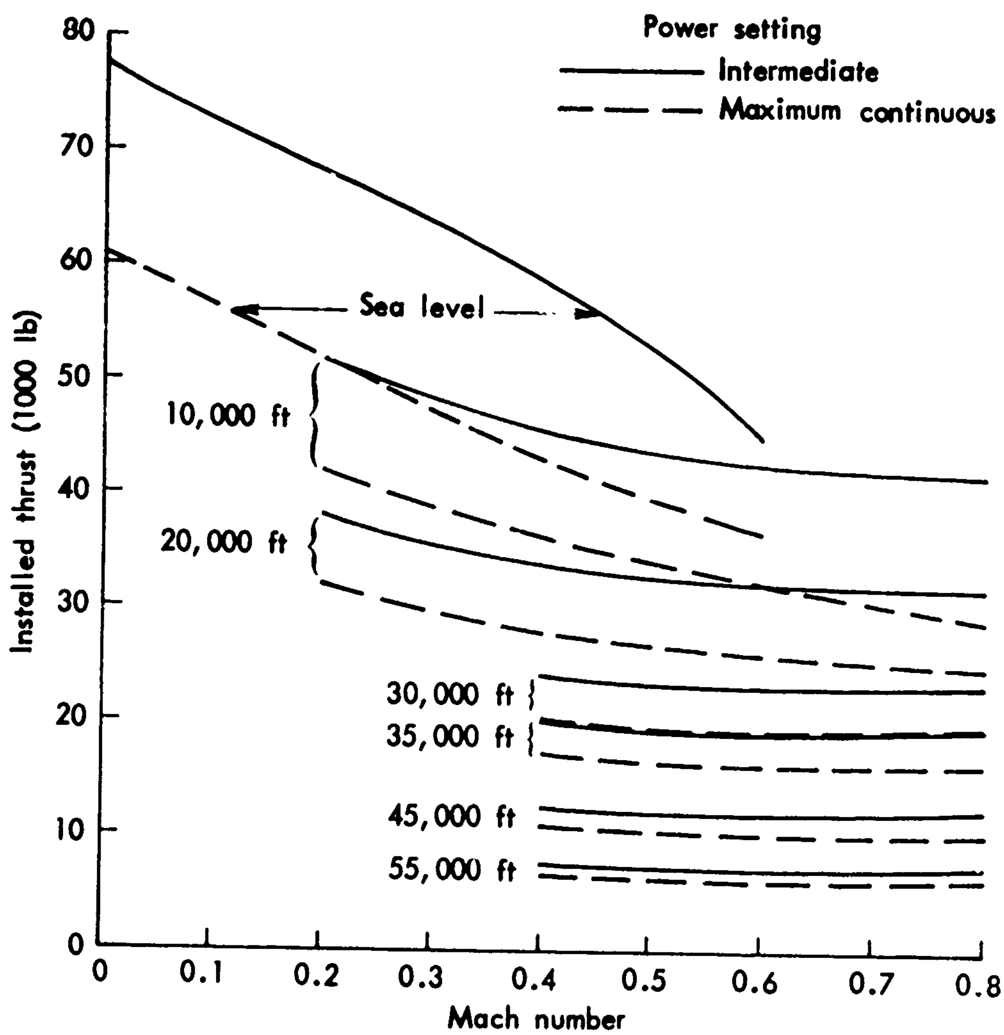

Fig. B-9—Installed thrust of the VLA-NUC dual-mode engine at selected altitudes -- JP mode

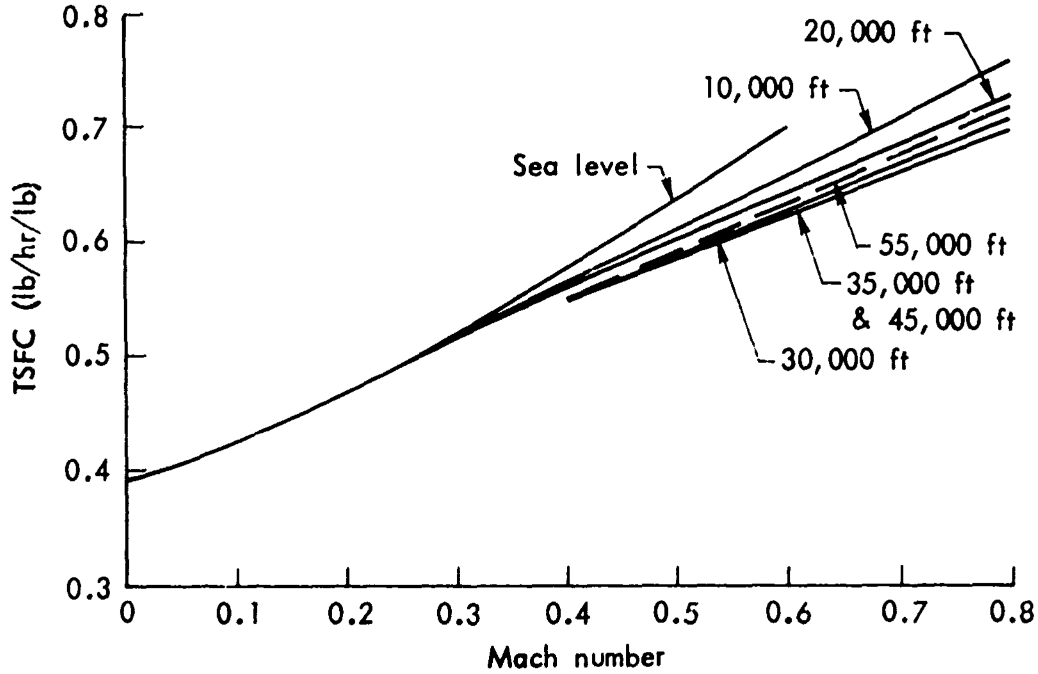

Fig. B-10—Installed thrust-specific fuel consumption of the VLA-NUC dual-mode engine -- JP mode at intermediate power

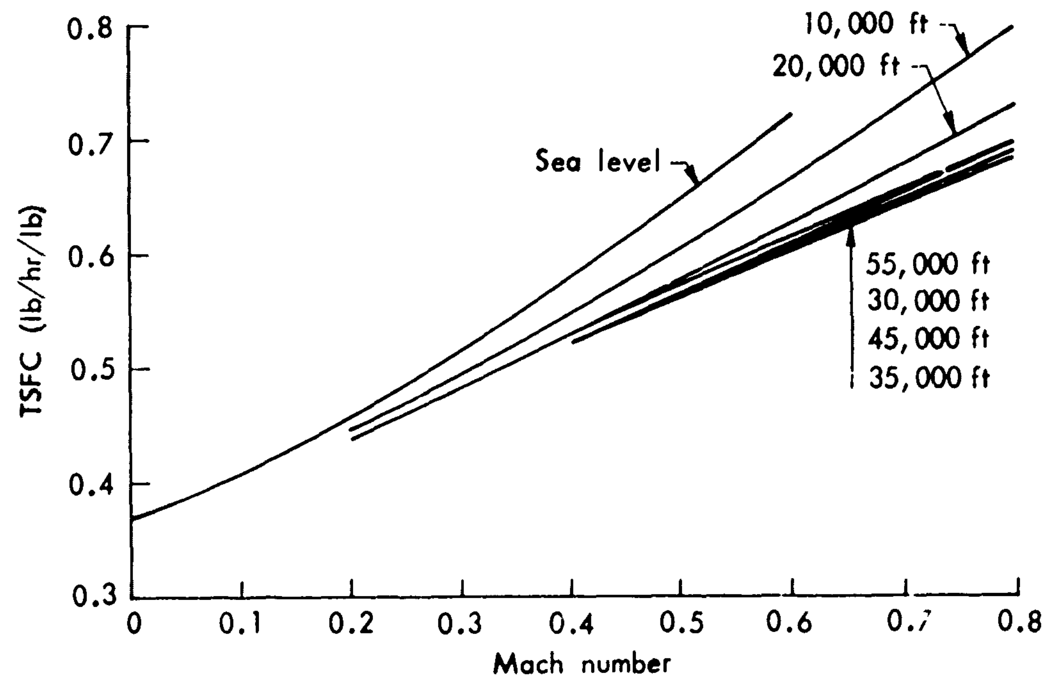

Fig. B-11—Installed thrust-specific fuel consumption of the VLA-NUC dual-mode engine -- JP mode at maximum continuous power

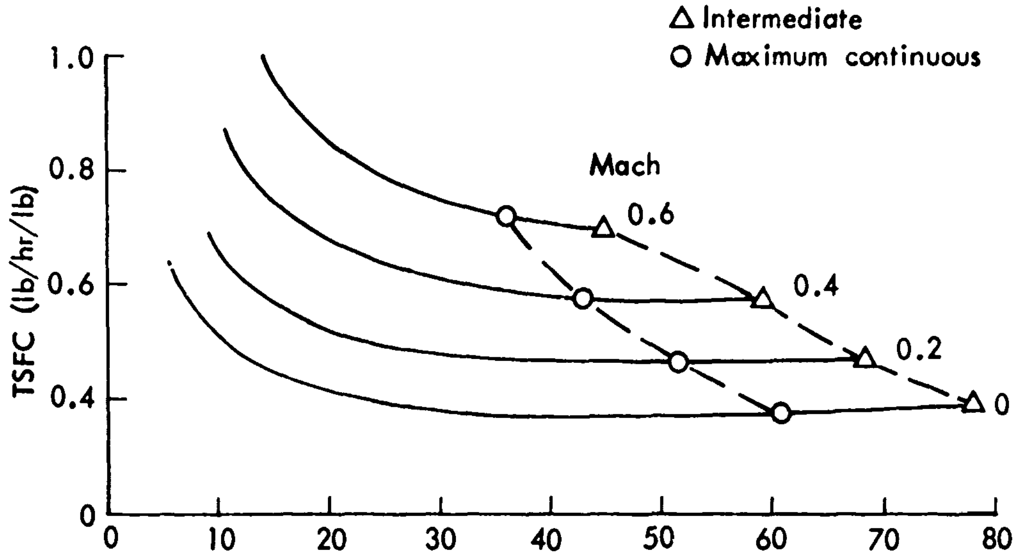

Fig. B-12a — Installed performance of the VLA-JP dual-mode engine -- JP mode at sea level

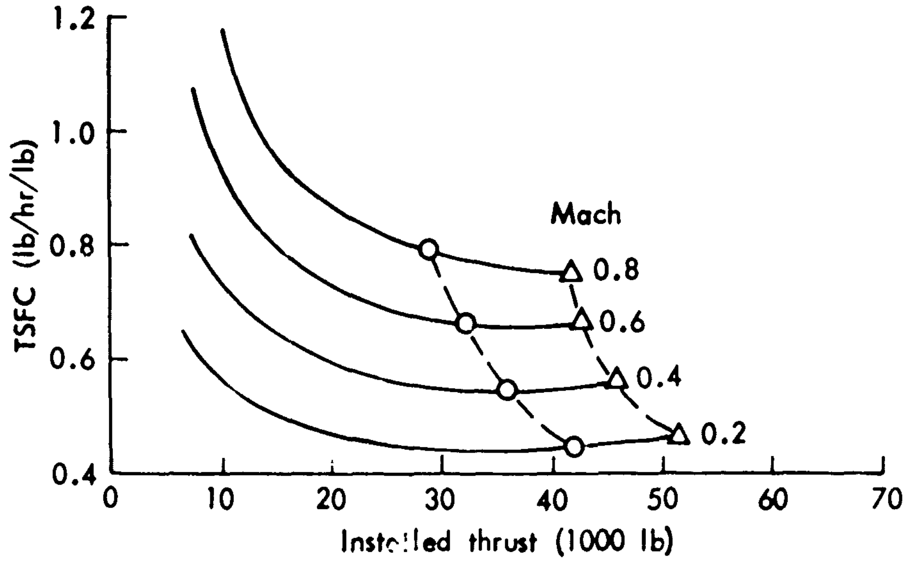

Fig. B-12b — Installed performance of the VLA-NUC dual-mode engine -- JP mode at 10,000 ft

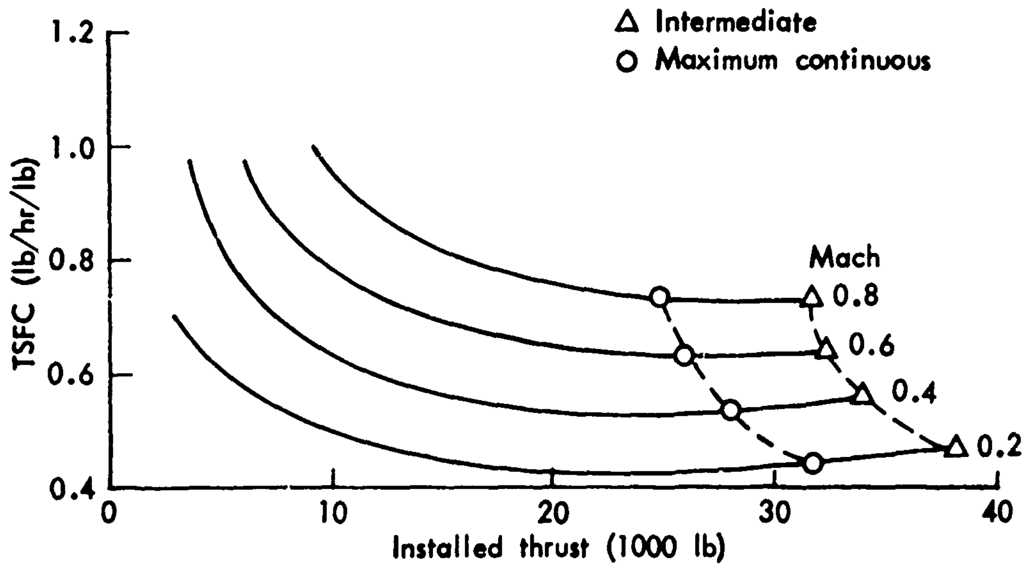

Fig. B-12c—Installed performance of the VLA-NUC dual-mode engine -- JP mode at 20,000 ft

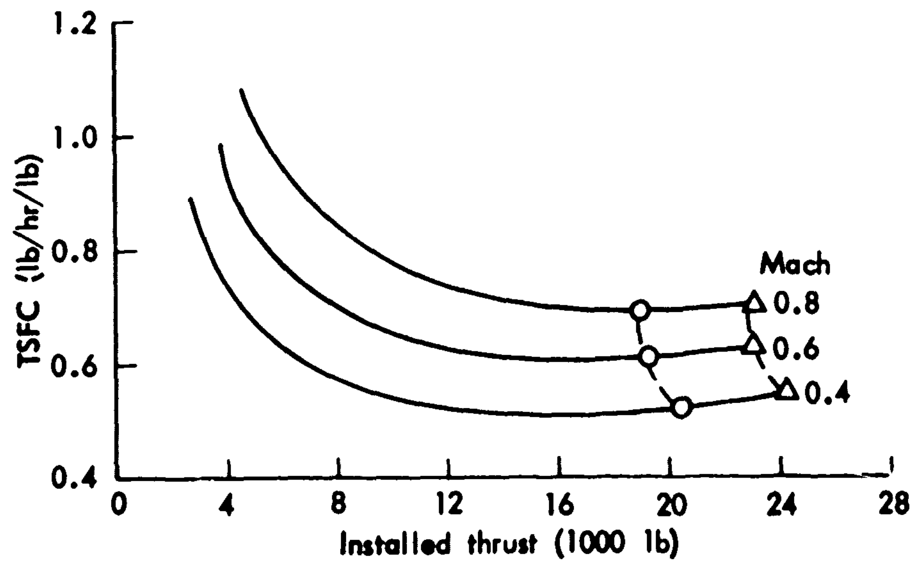

Fig. B-12d—Installed performance of the VLA-NUC dual-mode engine -- JP mode at 30,000 ft

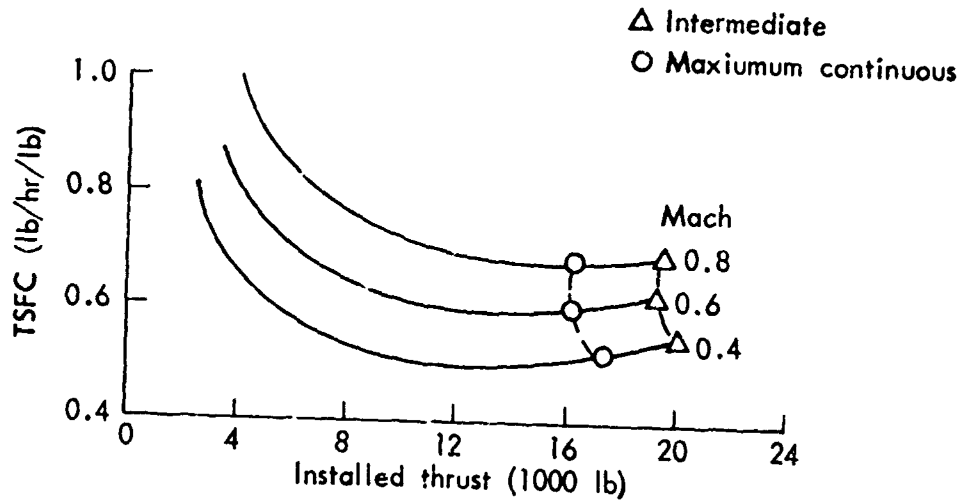

Fig. B-12e — Installed performance of the VLA-NUC dual-mode engine -- JF mode at 35,000 ft

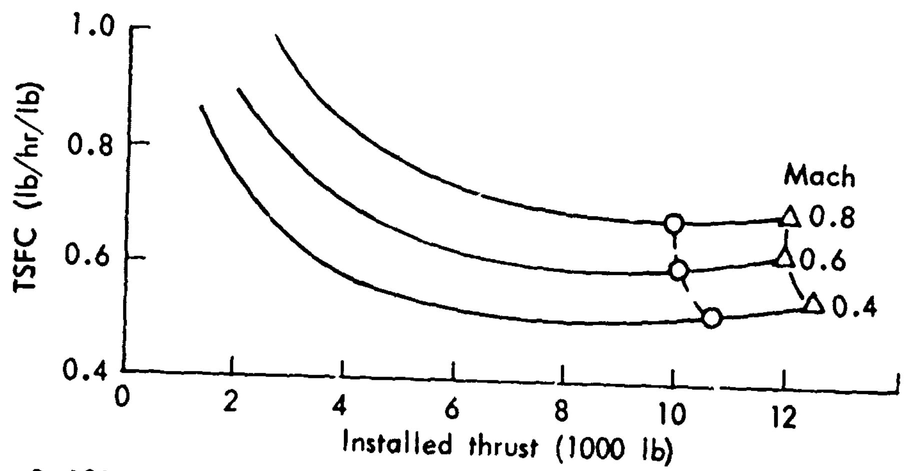

Fig. B-12f — Installed performance of the VLA-NUC dual-mode engine -- JP mode at 45,000

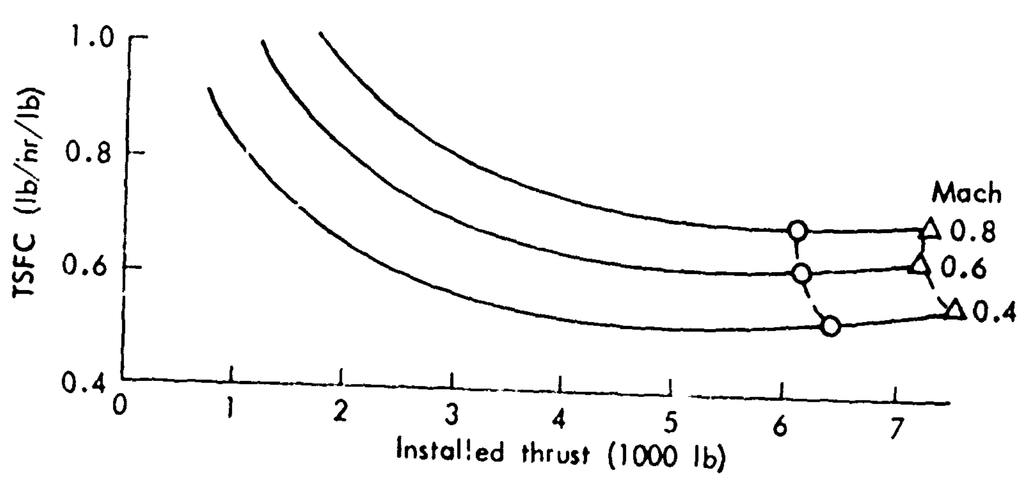

Fig. B-12g — Installed performance of the VLA-NUC dual-mode engine -- JP mode at 55,000 ft

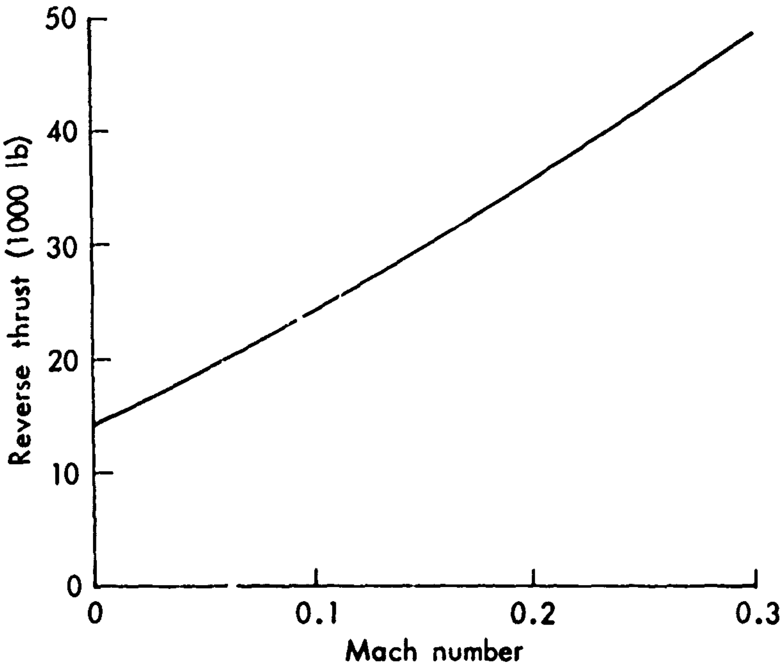

Fig. B-13 —Reverse thrust of the VLA-NUC dual-mode engine -- JP mode

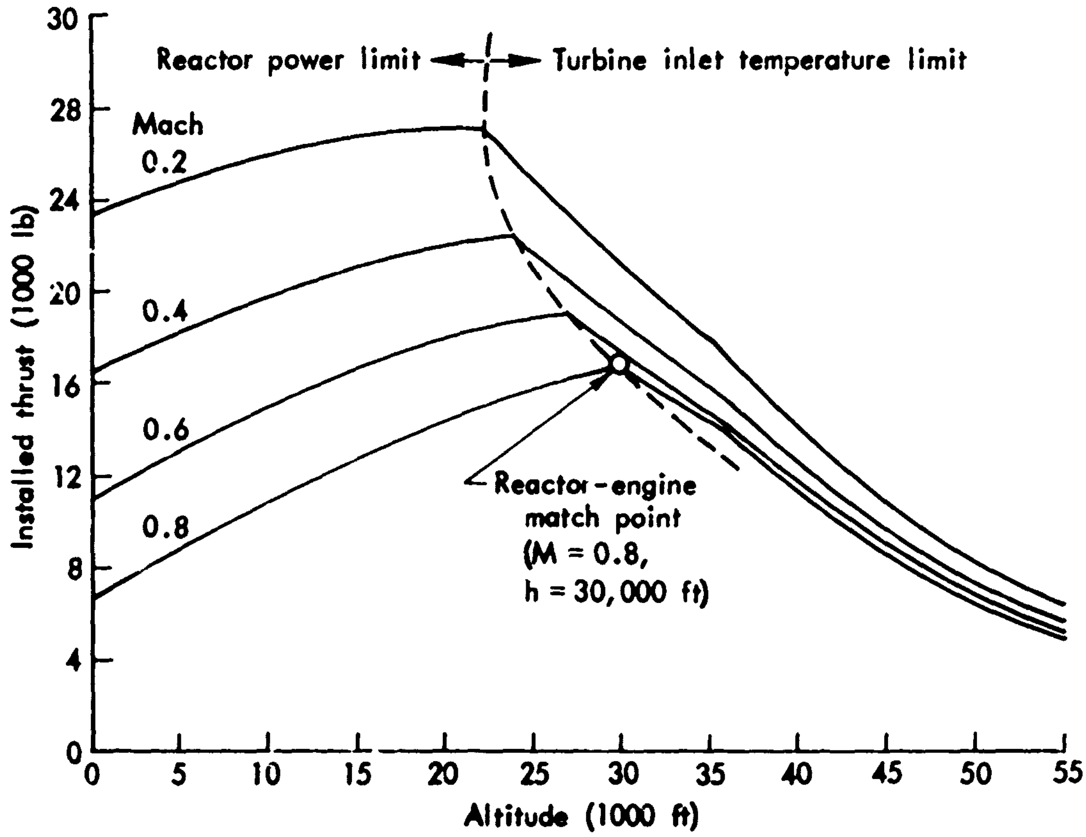

Fig. B-14—Installed performance of the VLA-NUC dual-mode engine -- nuclear mode

Nuclear System

A liquid-metal-cooled fast-reactor system was chosen for examination in this study simply because parametric sizing methodology and data were readily available for this concept. The only other reactor concept presently identified as competitive is the helium-cooled graphite-moderated reactor [78,79,80]; however, this concept has not been investigated to the level that the liquid-metal concept has, and parametric sizing methodology and data are lacking.

The nuclear system--including the reactor, shielding, containment vessel, primary heat exchangers, and associated equipment--are based on a Westinghouse parametric design formulated during an earlier study [78]. Characteristics of the liquid-metal-to-air heat exchangers are derived from the previously mentioned UARL work [76].

Dimensional and weight data for the reactor system (i.e., all components within the containment vessel) can be determined from the Westinghouse study for any given power-level reactor. However, we modified these results so that the JP required for emergency cruise could be utilized as partial shielding. This afforded a reduction in shield weight and in the physical size and weight of the containment vessel. The magnitudes of these reductions were derived from the original Westinghouse shielding thickness and weight data. Table B-6 summarizes the resulting system characteristics for the two nuclear-powered aircraft. The reductions in shield and containment-vessel size and weights made possible by using the emergency JP for neutron shielding are probably optimistic since the concept cannot be implemented on a one-for-one basis (i.e., replacing one pound of inner neutron shield with one pound of JP fuel). This occurs because the neutron shield is interior to the gamma shield and a reduction in its thickness increases the number of neutrons absorbed in the gamma shield and hence the production of secondary gammas. Thus, reducing the thickness of the inner neutron shield necessitates increasing the thickness of the gamma shield to attenuate secondary gammas and alters the neutron flux level at the surface of the gamma shield. Aside from the greater numbers, the energy distribution of neutrons escaping from the surface gamma shield will be skewed towards

Table B-6

CHARACTERISTICS OF THE NUCLEAR SYSTEMS

Parameter	VLA-NUC	VLA-NUC*
Number of reactors	1	1
Reactor power (MWt)	535	390
Average fuel burn-up rate (%)	11.4	11.4
Outlet temperature (°F)	1,900	1,900
Operating lifetime (full-power hr)	10,000	10,000
Dose range (millirem/hr[a])	5	5
Impact velocity[b] (ft/sec)	300	300
Containment vessel and contents weight[c] (lb)	471,702	403,291
Containment vessel diameter (in.)	201.88	192.07
JP weight[d] (lb)	117,407	113,838
JP tank diameter[d] (in.)	255.0	246.5

[a]One rem is the dosage of an ionizing radiation that will cause the same biological effect as one roentgen of X-ray or gamma ray dosage.

[b]Design point for assumed crash containment.

[c]See Table B-8 for complete nuclear system weight statement.

[d]Emergency-cruise JP used as partial shielding.

higher energies, since an average neutron will not have lost as much energy in collisions with the nuclei of the inner neutron shield material as it would have without a reduction in the inner shield thickness. The net result is that a greater thickness of auxiliary shielding (JP in this case) is required to attenuate the radiation emanating from the gamma shield surface. Despite an increase in total shield weight, the overall propulsion system weight is decreased because the emergency JP fuel must be carried whether or not it is used

in the shield. Hence any shield material removed is a weight savings.[a] A detailed shield design analysis is required to define fully the weight savings, but such an analysis is beyond the scope of this study.[b]

The weight and dimensional data for the liquid-metal-to-air heat exchangers are based on data derived by UARL. Weights and dimensions for representative canned motor-pumps and the generators required to pump the liquid metal in the secondary loop were derived by ASD; so were the weights for the reactor-shield cooling system and for piping and insulation.

Dimensional and weight data for all major components of a nuclear propulsion system, excluding the turbofan engines, were generated for a 203-MW reactor. By then defining a scaling factor (SF) as

$$SF = \frac{n_e T_e}{236,684} \qquad \text{(B-4)}$$

where

n_e - number of engines

T_e - maximum sea-level static thrust per engine (nuclear mode),

we were able to calculate the variations in component weights and dimensions for the reactor required by a specific aircraft design. The scaling process is illustrated in Table B-7. Table B-8 is the resulting weight breakdown for the complete nuclear systems of the VLA-NUC and VLA-NUC*, excluding the weights of the dual-mode turbofan engines.

---

[a] A secondary benefit of reducing the thickness of the inner neutron shield is the reduction in containment-vessel diameter and weight made possible by a smaller reactor pressure vessel (assuming the JP shielding is exterior and concentric to the containment vessel).

[b] The emergency JP is only required in situations in which the reactor is operating at less than full power (and usually only when it is completely shut down). Under these circumstances the shielding requirement is less stringent.

Table B-7

SCALED WEIGHT AND DIMENSIONAL CHARACTERISTICS
FOR NUCLEAR SYSTEM COMPONENTS

Component	Scaled Value
Reactor and containment vessel	
Maximum power (MWt)	SF x 203
Weight	See Fig. B-15a
Diameter	See Fig. B-15b
Radiator and NaK (NaK-to-air)	
Weight (lb/engine)	SF x 4280
Dimensions	Included in engine
Piping and NaK (including insulation)	
Weight (lb/linear ft)	$SF^{0.95}$ x 47.6
Diameter (in.)	See Fig. B-16
Canned motor - pump and sump	
Weight (lb/engine)	SF x 487.5
Diameter (in.)	$(SF \times 18{,}018)^{1/3}$
Length (in.)	1.485 x diameter
Generator and gearbox	
Weight (lb/engine)	SF x 198
Diameter (in.)	$(SF \times 198)^{1/3}$
Length (in.)	1.692 x diameter
Reactor shield cooling system	
Radiator--2 required (lb)	SF x 922
Motor-pump--1 required (lb)	SF x 136
Piping and NaK (lb/linear ft)	$SF^{0.95}$ x 5.66
JP used for shielding	
Weight (lb)	See Fig. B-15a
Outside diameter (in.)	See Fig. B-15b

Table B-8

WEIGHT BREAKDOWN OF NUCLEAR SYSTEMS
(lb)

	VLA-NUC	VLA-NUC*
Reactor and containment vessel	471,702	403,291
Piping and NaK coolant	71,349	47,210
Radiator and NaK coolant	90,070	65,690
Motor and pump for NaK	10,258	7,482
Generator, gearbox, and shafting	4,166	3,039
Piping and NaK (shield cooling)	1,189	814
Radiator and NaK (shield cooling)	2,425	1,769
Motor and pump for NaK (shield cooling)	358	261
Total nuclear system	651,517	529,556
JP used for shielding	117,407	113,838

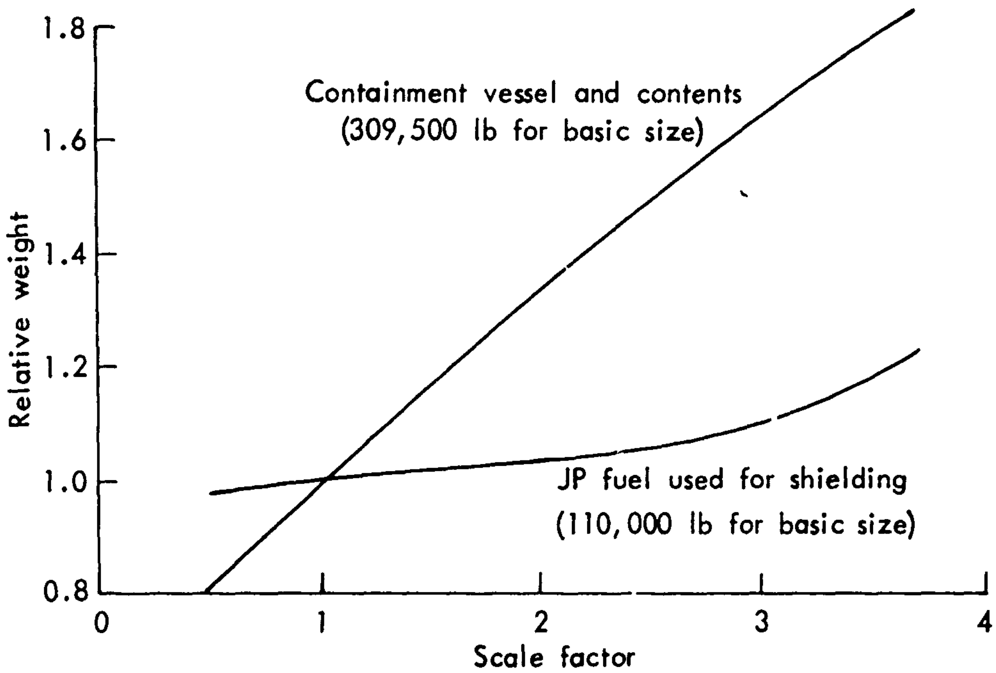

Fig. B-15a—Weight scale factors for a JP-shielded reactor system

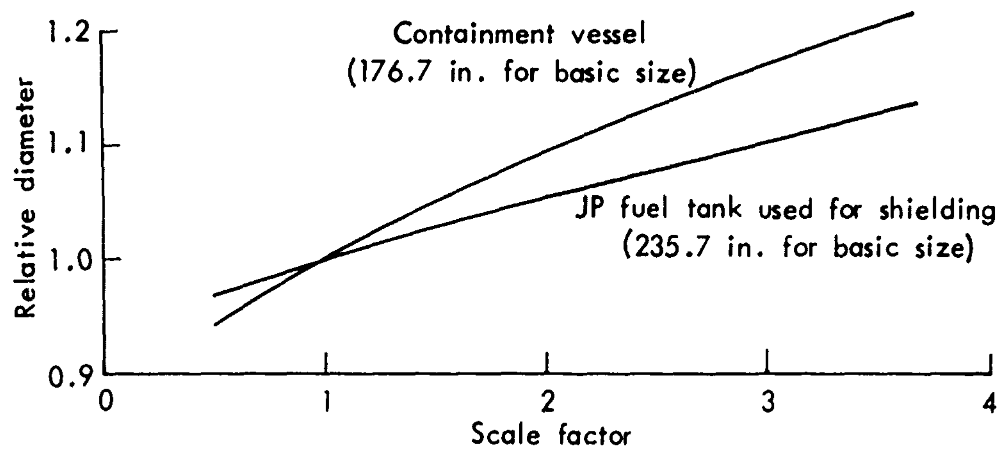

Fig. B-15b—Diameter scale factors for a JP-shielded reactor system

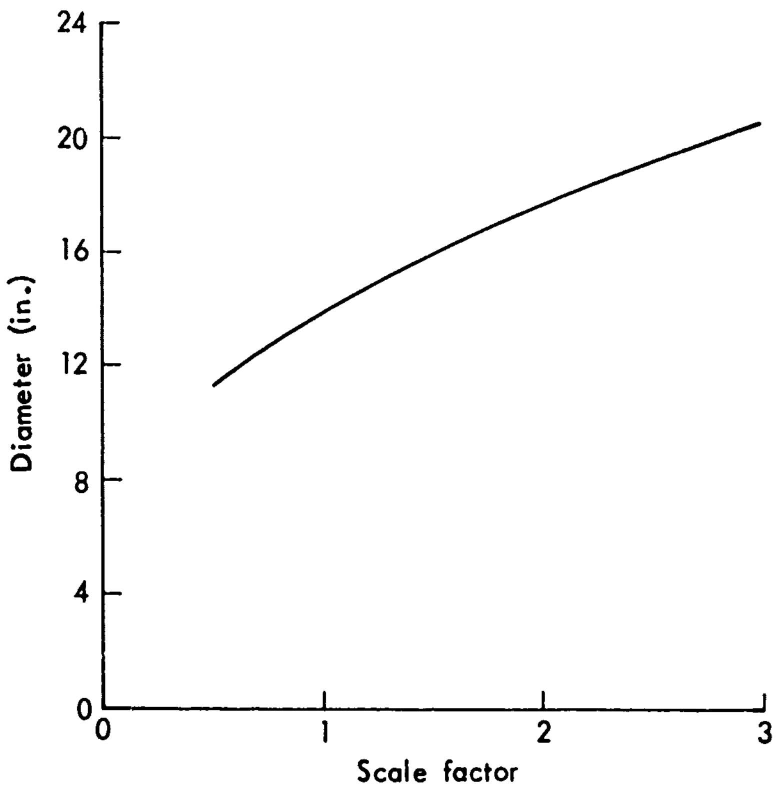

Fig. B-16—Scale factor for piping and NaK components

Appendix C

PERFORMANCE OF THE CHEMICAL-FUELED ALTERNATIVES WITH IN-FLIGHT REFUELING

Among the potential applications of very large airplanes mentioned in Section II are the tanker missions. We noted that very large airplanes could be used for the in-flight refueling of airlifters, tactical fighters, or strategic bombers.

In the latter two applications, it would seem logical to assume that the fighters or bombers will be JP-fueled.[a] Thus, regardless of the fuel employed in the tanker, it will be transferring JP to the receiver aircraft. Although we have not explicitly analyzed these two mission applications, insights into the performance of the alternative VLAs can be gained from data presented in Appendix A. For example, Fig. A-3 contains the payload-radius trade-off and Fig. A-4 the endurance-radius trade-off (at several payloads) for the VLA-JP aircraft. Such information, coupled with the associated tanker weight increments given in Table A-2, can be employed to estimate the minimum fuel (JP) off-load characteristics for different transfer radii and mission rules. (See also the discussion in Section IV.)

Of greater interest in the present work is the performance of the VLA alternatives when refueled in flight by tanker versions of the same basic airplane. This appendix gives these performance characteristics for the alternative very large airplanes and also for two proposed versions of the Lockheed C-5B. First, however, we will briefly describe our technique for calculating how these airplanes perform with in-flight refueling.

---

[a]Logical in the sense that throughout this work we have assumed that the initial application of cryogenic fuels would be in transport category aircraft.

THEORETICAL APPROACH

Airplane performance with in-flight refueling is a potentially complex problem and depends on the aerodynamic, propulsion, and weight characteristics of the tanker and receiver aircraft. To determine it, we have employed a greatly simplified technique that assumes the foreknowledge of at least two points on the range-payload curve for both tanker and receiver. These curves for the VLA alternatives are given in Appendix A; comparable data are generally available for most existing [81] and proposed aircraft [82,83,84].

The equations of motion for a turbine-powered airplane can be integrated to obtain the following close approximation for the airplane's range.

$$R = \frac{a}{c_t} M_\infty \, (L/D) \, \log_e \left(\frac{W_0}{W_1}\right) \tag{C-1}$$

where

- R - range
- a - speed of sound
- c_t - thrust specific fuel consumption (TSFC)
- M_∞ - cruise Mach number
- (L/D) - lift-to-drag ratio
- W_0 - gross weight at initial cruise altitude
- W_1 - gross landing weight

Of course, Equation C-1 is simply a version of the well-known Breuget range equation [85]. For high altitude flight employing a cruise-climb profile, results obtained with Equation C-1 are almost exact (depending on airplane configuration) except for the relatively small effect of altitude changes on the speed of sound and specific fuel consumption; TSFC also varies slightly since the thrust required decreases (at constant L/D) as the cruise phase proceeds.[a] Our approach has been to express Equation C-1 as

[a]The speed of sound decreases by about 2.7 percent from 30,000 ft to 36,000 ft; above 36,000 ft, the speed of sound is constant. Figures B-2 and B-3 illustrate the relative insensitivity of specific fuel consumption (at constant power) to changes in altitude, and Fig. B-4 depicts the variation in TFSC with thrust level.

$$R = \text{fcn}\ (W_G, P, W_E) \qquad \text{(C-2)}$$

where

W_G - gross takeoff weight

P - payload weight

W_E - operating empty weight

Algebraic manipulation of Equation C-1 yields the following equations:

$$R = k_B \log_e \left[\frac{W_G \dfrac{W_c}{W_g}}{W_E + P} \right] \qquad \text{(C-3)}$$

with

$$W_c = \left[\frac{\left(W_e + P_y\right)^{R_x/R_y}}{W_e + P_x} \right]^{\frac{1}{R_x/R_y - 1}} \qquad \text{(C-4)}$$

and

$$k_B = \frac{R_x}{\log_e \left[\dfrac{W_c}{W_e + P_x} \right]} \qquad \text{(C-5)}$$

where

R_x, P_x - range and payload at the X-point

R_y, P_y - range and payload at the Y-point

W_g - gross takeoff weight associated with the X-point and Y-point

W_e - operating empty weight associated with the X-point and Y-point

Thus, if any two points of the range-payload curve are known (preferably the X-point and Y-point as defined in Section II), then Equations C-3 through C-5 fully specify the curve if

$$W_G = \begin{cases} W_{G_{max}}, \text{ if } P > P_y \\ W_{G_{max}} - (P_y - P), \text{ if } P \le P_y \end{cases} \qquad \text{(C-6)}$$

where

$W_{G_{max}}$ - maximum gross takeoff weight for the limit load factor of interest

The equations presented above can also be used to develop the radius-payload curve and range/radius characteristics with aerial refueling. (Tanker performance can similarly be estimated using Equations C-3 through C-5.)

For example, radius mission performance (for a given payload) is determined by assuming initially that one-half of the available mission fuel is required for the return leg. Equations C-3 through C-5 can be employed to calculate an outbound range by including the return fuel in the denominator of Equation C-3; the corresponding inbound range is calculated by replacing W_G with the empty weight plus the return fuel weight. Iterating on different assumed values for return fuel will ultimately provide an outbound range equal to the inbound range--in other words, the mission radius.

Performance with in-flight refueling can similarly be estimated. With buddy mission rules,[a] for example, Equations C-3 through C-5 can be used to calculate fuel burn-off as a function of distance out for the receiver and fuel off-load capability as a function of radius for the tanker. The intersection of these curves yields the transfer point (distance out) and the range or radius of the airlifter can then be determined as described above. In the case of rendezvous missions, the fuel off-load capability of the tanker at a given radius is decreased by the amount of fuel required for a one-hour loiter. Optimum fuel transfer occurs at the point where (after the transfer) the receiver and tanker have just enough fuel to reach their destination. (In all our work, we have assumed that tankers and airlifters originate at the same base for buddy missions--with the tanker returning to the originating base--and have the same destination for rendezvous missions--with the tanker flight originating at the destination base.)

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[a]As used in this report, "buddy-IFR" means that the airlifter receives an in-flight refueling on its outbound leg; a "buddy/rendezvous-IFR" includes also an in-flight refueling on the inbound leg.

A simple computer model has been constructed which, for a given tanker/airlifter pair, determines for the airlifter

- o Payload versus range/radius with no refueling
- o Payload versus range/radius with an outbound (buddy rules) refueling
- o Payload versus radius with an outbound refueling (buddy rules) and an inbound (rendezvous rules) refueling

Any assumed combination of tankers and airlifters in a flight (e.g., three tankers serving two airlifters) can be treated.

All of the results presented in this appendix have been calculated using this model.[a] Insights into the accuracy of this approach can be gained by comparing the radius mission results (no refueling) with those presented in Appendix A. For example, the curves in Fig. C-3 (p. 238) can be compared to the 2.25 g curves in Fig. A-3 (p. 164) for the VLA-JP.

LOCKHEED C-5B

In recent years, several new versions of the Lockheed C-5 have been advanced [82,83,84], some of them specifically intended to satisfy the requirements of the "Advanced Tanker/Cargo Aircraft" (ATCA) [86]. Unfortunately, each of these somewhat different versions of the basic C-5 aircraft has been generally referred to as the C-5B.

In the present study, we have used a proposed C-5 model designated by Lockheed-Georgia as the LG5-193A to represent the C-5B alternative [82]. More recently, Lockheed proposed a similar version designated as the LG5-194B [83].[b] We will describe both of these versions and compare their performance characteristics in order to illustrate that--at least for purposes of the present study--they are essentially identical.

---

[a]Note that this model implicitly incorporates any assumptions made in the initial determination of the range-payload curve. Thus, if MIL-C-5011 A rules were used to specify fuel reserves, etc. (as they have been throughout this report), then the model results will also reflect MIL-C-5011 A rules.

[b]The C-5B data in this report are based on preliminary Lockheed estimates.

<u>The LG5-193A</u>

Externally, the LG5-193A is very similar to the C-5A except that it has a tanker capability. Since using the C-5B as a tactical airlifter is not envisioned, the following equipment items are not included in the basic airplane:

- High-pressure pneumatic system
- Aft troop-compartment kit
- Cargo-compartment red lighting
- Paratroop kit
- Aerial delivery system kit
- In-flight tire deflation
- Energy management analog computer
- Integral weight and balance system

Certain of the C-5A avionics (e.g., the malfunction detection and recording system) are replaced by comparable commercial equipment. Of course, the LG5-193A incorporates major structural changes in the wing, changes that are equivalent to the wing modification currently planned for retrofit into the C-5A aircraft under the Service Life Management Plan [87].

The maximum gross weight of the LG5-193A is 769,000 lb (2.25 g[a]); the operating empty weight is 362,000 lb in the cargo mode and 360,800 lb in the tanker mode.

<u>The LG5-194B</u>

The LG5-194B configuration, as proposed by Lockheed-Georgia, is quite similar to that of the LG5-193A, with the following exceptions:

- Deletion of the leading-edge slats
- Deletion of the fire-protection system
- Replacement of the passive lift-distribution-control system with an active lift-distribution-control system

[a]Based on the ground-maneuver limit. The 769,000-lb gross weight corresponds to a flight-load factor of 2.50 g.

There are also some minor structural differences between the LG5-193A and the LG5-194B.

The LG5-194B as configured above would provide approximately 13 percent greater range for a given payload than the LG5-193A (no in-flight refueling). However, for our present purposes we believe that both the leading-edge slats and the fire-protection system (or its equivalent) should be retained.

Consider first, the leading-edge slats. Without these high-lift devices, the critical field length of the C-5B would be increased from 8000 ft to 9800 ft at maximum takeoff weight. Since the VLA design goal is 8000 ft, deleting the slats would overly bias any comparison in favor of the C-5B.

The fire-protection system was not original equipment on the C-5A. However, the Air Force has retrofitted the system to most operational airplanes. In light of this action, we think that some type of fire-protection system (perhaps coupled with additional design changes) would also be required on any new C-5 models that might be procured. We have chosen simply to retain the existing system.

The maximum gross weight of the modified LG5-194B is also 769,000 lb (2.25 g, ground-maneuver limit); the operating empty weight (with leading-edge slats and fire-protection system) is 367,000 lb in the cargo mode and 364,500 lb in the tanker mode.

Performance with In-Flight Refueling

Figure C-1 compares the payload performance of the LG5-193A and the modified LG5-194B for various range and radius missions. Depending on the mission profile, the LG5-194B provides from 3 to 15 percent greater payload at a given range or radius than the LG5-193A.[a]

We have based our work on the proposed LG5-193A despite its modestly inferior performance. All our analytical work concerning the C-5B had been completed before the LG5-194B data were available to us. Given the

[a]The superior performance of the LG5-194B can be largely attributed to its employing an active rather than passive lift-distribution-control system.

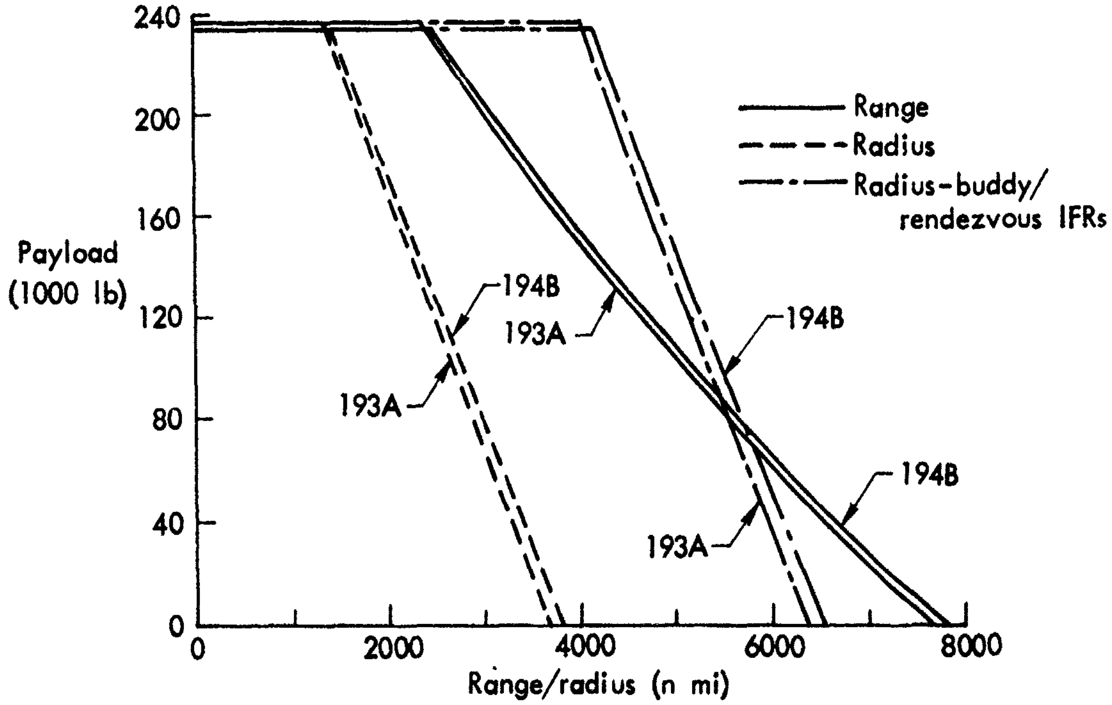

Fig. C-1—Performance comparison for C-5B models designated LG5-193A and LG5-194B

similarity of these two proposed airplanes, redoing this element of the analysis did not appear worthwhile. We feel that using the LG5-193A in place of the LG5-194B will not cause any significant differences in the comparisons made between the C-5B and the very large airplane alternatives in the main text. Actually, were the Air Force to procure C-5Bs, the airplane selected for production would almost certainly differ from either of these proposed versions. Thus, the LG5-193A seems appropriate as a representative contemporary large airplane.

Complete performance characteristics for the C-5B with in-flight refueling is shown in Fig. C-2. We should note that the maximum gross weight of the C-5B was assumed to be 769,000 lb in the cargo mode, but

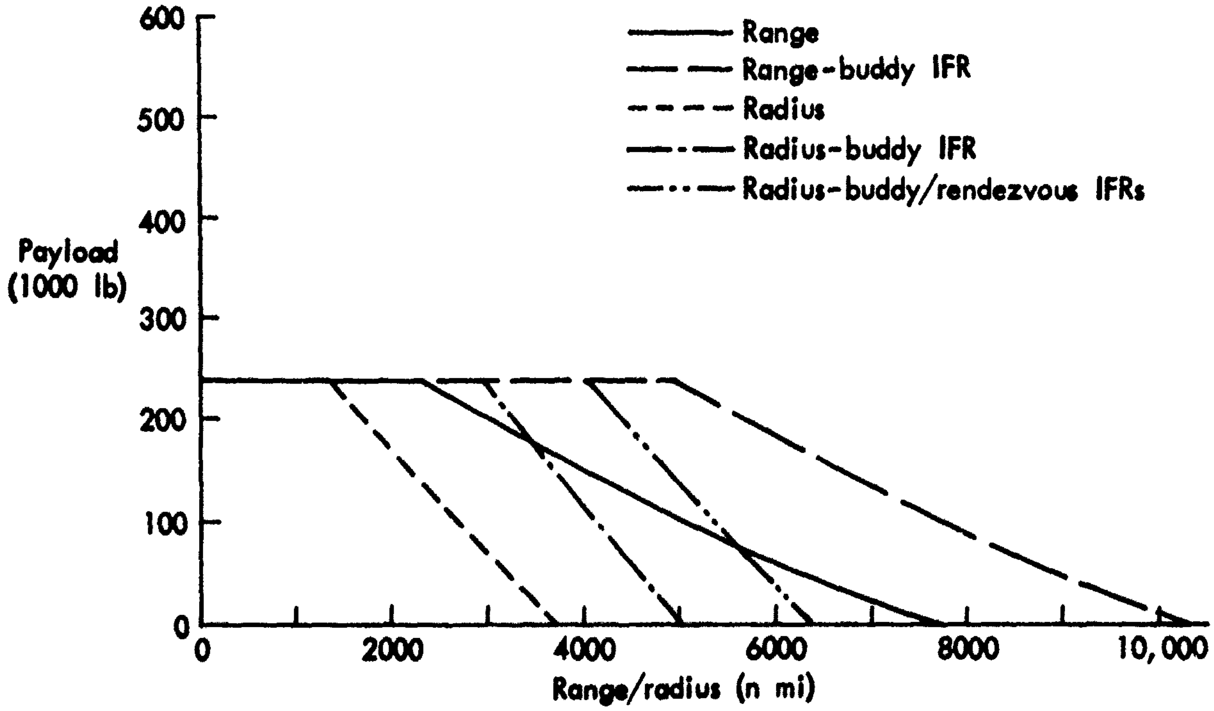

Fig. C-2—C-5B (LG5-193A) performance with in-flight refueling

was increased to 795,000 lb for C-5Bs operating in the tanker mode. This latter figure is based on a load factor of 2.00 g (again, a ground-maneuver limit). KC-135As routinely operate at this reduced (flight) load factor [81] and it therefore seemed appropriate to use this less conservative value.

VERY LARGE AIRPLANES

Modifications to the basic VLA designs that allow the airplane to serve in the tanker/cargo role are detailed in Appendix A. As noted earlier, these modifications presume that JP is the fuel being transferred--regardless of what fuel the very large airplane is using. Thus, the characteristics of the VLA-JP in the tanker mode are fully specified, but additional definition is required for the other alternatives since they must transfer a cryogenic fuel in the present application.

VLA-JP Alternative

The weight increment that must be added to the VLA-JP aircraft when serving in the tanker mode is detailed in Table A-2. In the tanker mode, the operating empty weight increases to 798,857 lb.

Performance for the VLA-JP with in-flight refueling is shown in Fig. C-3. Results in Fig. C-3 are based on a VLA-JP in the cargo mode being refueled by a VLA-JP configured in the tanker mode. We have also assumed that both tanker and airlifter operate at a maximum gross weight of 1.839 million lb which corresponds to the 2.25 g load factor. To have reduced the tanker load factor to 2.00 g (as was done for the C-5B) would have been largely superfluous since the VLA-JP can deliver its maximum payload of 550,000 lb on a radius mission in excess of 6000 n mi (with an outbound and an inbound IFR) as shown in Fig. C-3. (Recall from Section II how few applications require a mission radius greater than 6500 n mi.) Furthermore, increasing the gross takeoff weight of the VLA-JP tanker might preclude its operating from the same airfield as the airlifter, either because it might require greater takeoff field length and/or increased runway strength.

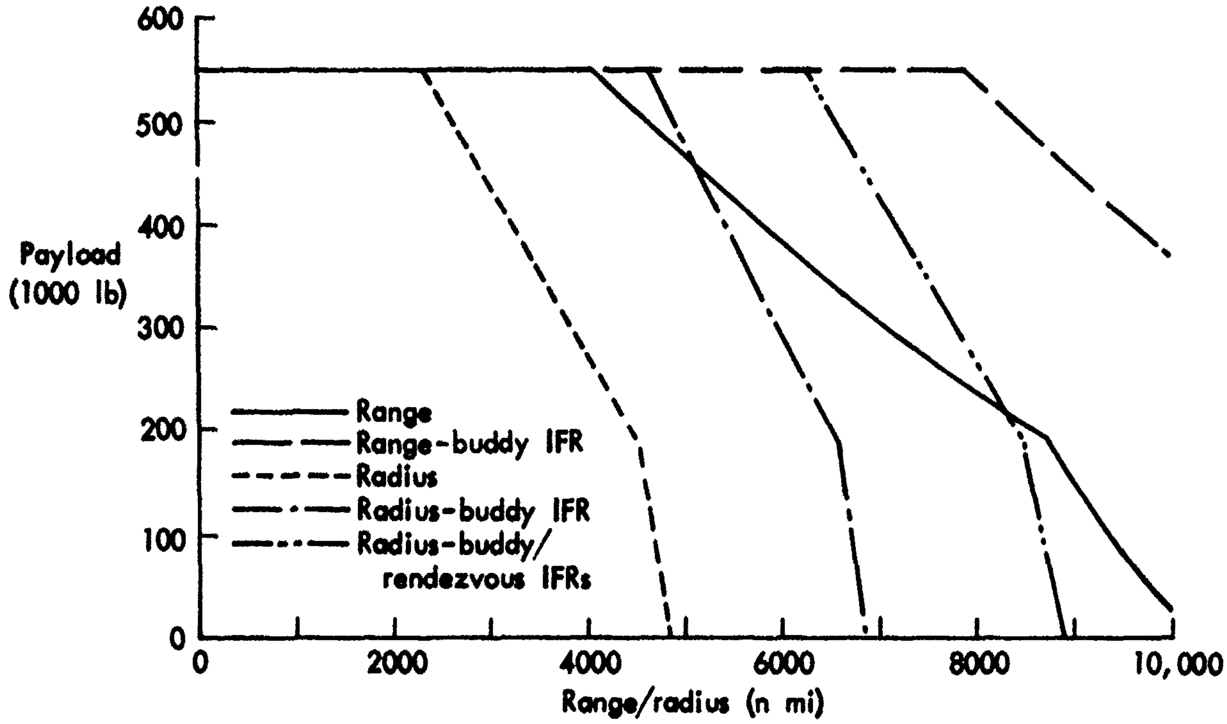

Fig. C-3—VLA-JP performance with in-flight refueling

Cryogenic-Fueled Alternatives

As noted earlier, the weight increments for VLAs in the tanker mode presented in Table A-2 presume that JP is being transferred. For the cryogenic-fueled VLAs, however, these weights must be modified if the respective cryogenic fuel is to be transferred to a VLA of the same type. Specifically, one must take into account the weight of the cryogenic tanks for the additional fuel carried aboard the tanker.

Table C-1 presents modified weight statements for the cryogenic-fueled tankers. For the VLA-LCH_4 alternative, the cryogenic tank

Table C-1

MODIFIED WEIGHTS OF VLA TANKERS TRANSFERRING CRYOGENIC FUEL

Weight Element	VLA-LCH_4	VLA-LH_2	VLA-LH_2*
Operating empty weight of cryogenic tanker with cryogenic tank in cargo compartment	(891,062)	(752,808)	(967,720)
- JP tanker	877,601	709,017	915,171
- cryogenic tank	13,461	43,791	52,549
Total usable fuel	(972,938)	(440,198)	(624,834)
- fuel in basic tanks	641,658	221,242	362,088
- fuel in additional tanks	331,280	218,956	262,746
Maximum gross weight of cryogenic tanker	1,864,000	1,193,006	1,592,554

is cylindrical and can easily be accommodated by the cargo compartment. The liquid-hydrogen tanks are assumed to have a semi-circular cross section so that the cargo compartment volume is more fully utilized. Even with this configuration which is less than desirable, from the point of view of the tank's construction, neither LH_2 airplane has sufficient fuel volume capacity to attain the 2.25-g-limited gross weight. (That the LH_2 airplanes in the tanker mode are so limited provides additional rationale for not reducing the flight load factors of the VLA-JP or VLA-LCH_4 tankers to 2.00 g. To do so would

introduce an unwanted bias that might hamper the comparison of the VLA alternatives.)

Corresponding performance characteristics of the VLA-LCH_4 are shown in Fig. C-4. Figure C-5 and Fig. C-6 present similar results for the VLA-LH_2 and VLA-LH_2*, respectively.

An interesting aspect of liquid-hydrogen-fueled airplanes emerges when one compares Figs. C-3 and C-5: the performance of the VLA-LH_2 with aerial refueling is generally superior to that of the VLA-JP. For example, the VLA-LH_2 with the design payload of 350,000 lb and a single outbound refueling has a mission radius of about 6500 n mi--almost 1000 n mi greater than the VLA-JP under the same circumstances. This occurs despite the aforementioned limitations on the maximum takeoff weight of the VLA-LH_2 in the tanker mode. The reason behind this phenomenon, of course, is that the additional fuel weight being carried on the VLA-LH_2 represents substantially greater fuel energy than the additional fuel aboard the VLA-JP.

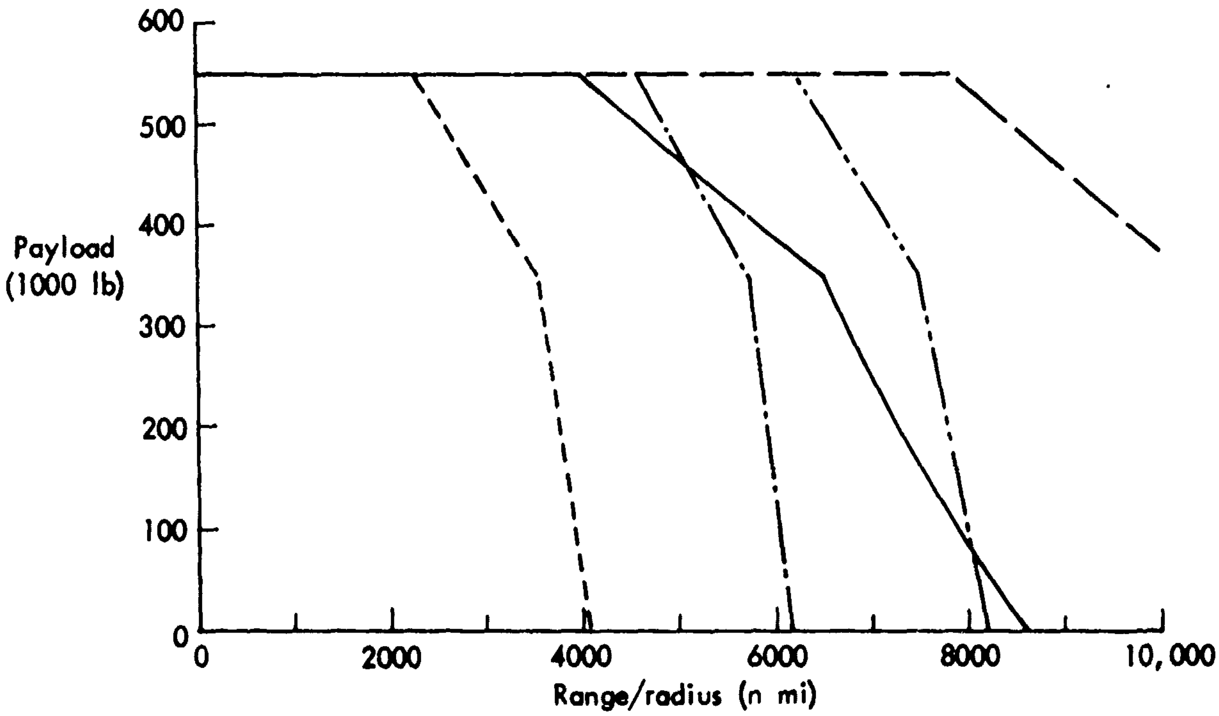

Fig. C-4—VLA-LCH_4 performance with in-flight refueling

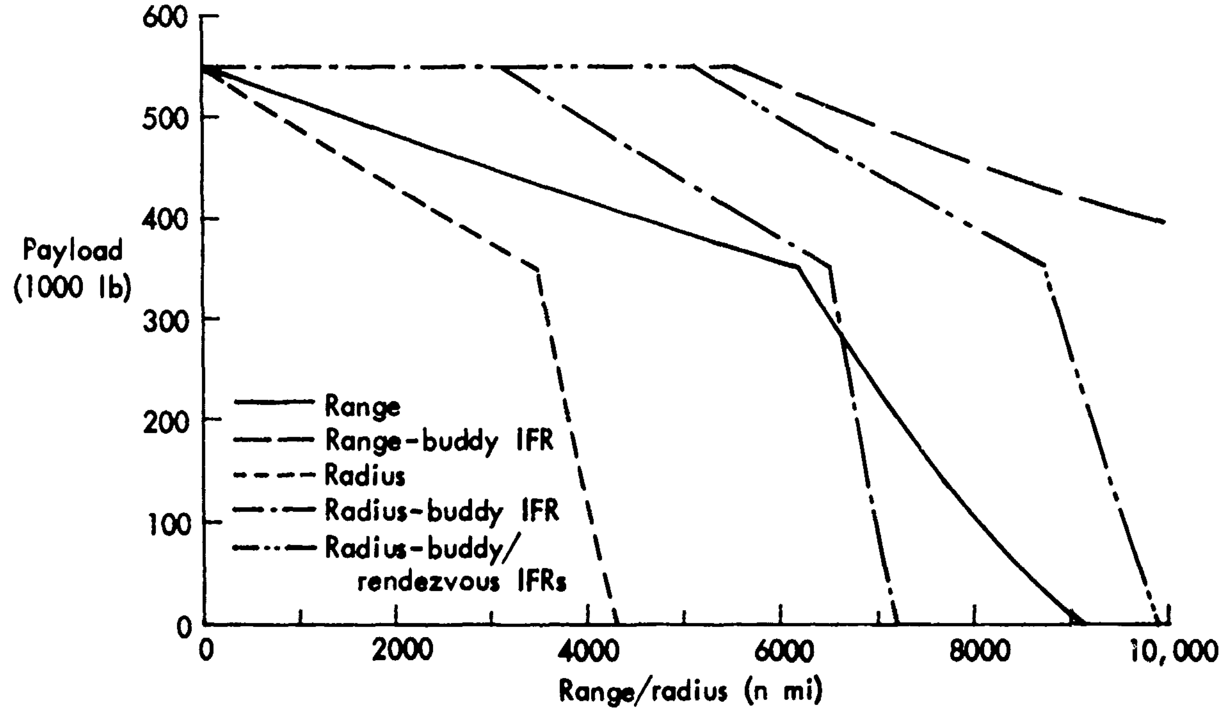

Fig. C-5—VLA-LH_2 performance with in-flight refueling

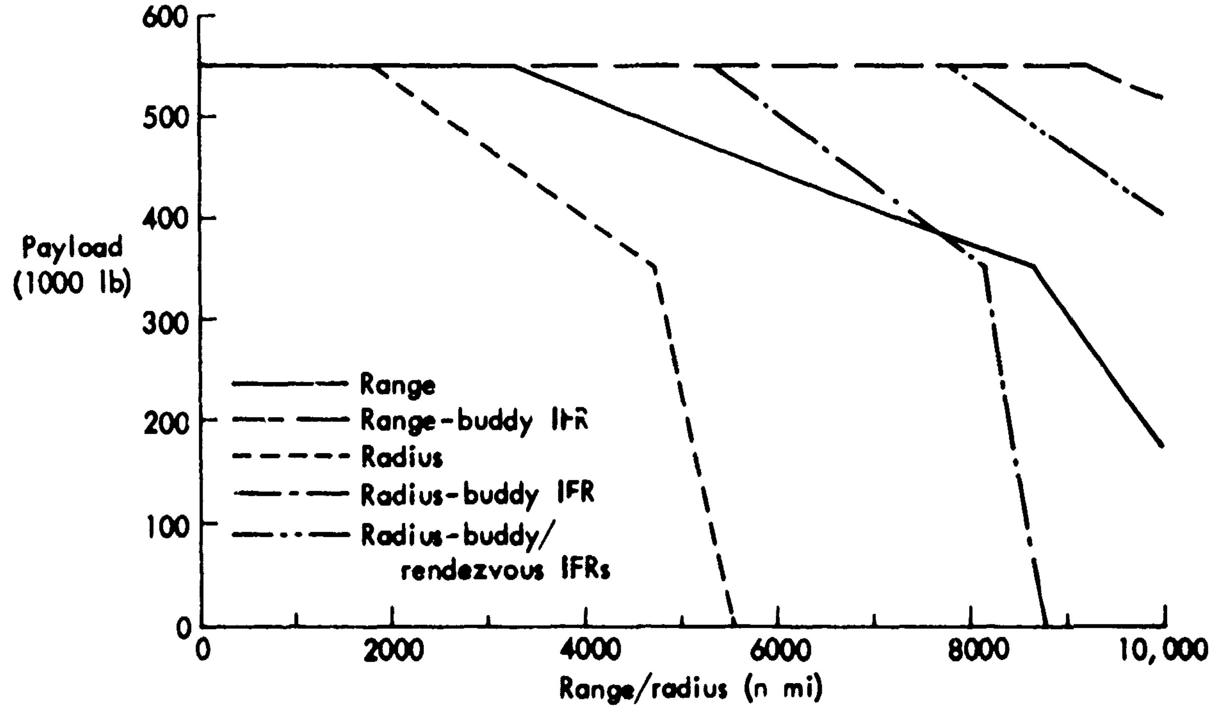

Fig. C-6—VLA-LH_2* performance with in-flight refueling

Appendix D

ESTIMATING LIFE-CYCLE COSTS

This appendix describes the methodology employed to estimate the life-cycle costs of the alternatives. The techniques for determining acquisition costs and operating and support costs (other than unit fuel costs) are presented. (Estimates for the average unit costs for the chemical fuels are reported elsewhere [19]; the basis of our nuclear fuel cost estimates is contained in Appendix E.)

Supplementary cost results are presented for each of the seven alternatives. These include the high, low, and nominal estimates of acquisition cost (in terms of the number of UE procured, as well as 20-year O&S costs for various assumed peacetime utilization rates). By combining this information, life-cycle costs can be developed for any number of UE and/or operational concepts. The methodological approach and results of ASD's independent cost analysis are also presented.

METHODOLOGY

The techniques for estimating aircraft acquisition costs are relatively well developed. For the present study, we used the most recently available Rand models for airframe and engine costing. Other acquisition cost elements were derived from recent Air Force experience in the procurement of transport aircraft.

Techniques for determining operating and support costs are less well defined. We have largely based the nonfuel O&S costs on an extrapolation of current USAF experience with the C-141A and C-5A aircraft.

Acquisition Costs

We first discuss the techniques for estimating development and production costs of airframes, engines, avionics, and nuclear reactor systems. These production costs account for the total flyaway cost.

Also described is the method employed to estimate other acquisition costs such as initial spares.

Airframe. Improved cost estimating relationships for airframe acquisition have recently been developed by Large, et al. [88]. In that work, regression analyses are presented which express airframe production costs in terms of AMPR (Aircraft Manufacturer's Planning Report) weight (i.e., the bare airframe weight), maximum flight speed, and quantity produced. Similar equations for the total development (RDT&E) costs are also included.

Table D-1 illustrates cost estimates for the VLA-JP airframe using four distinct methods.[a] Method 1 is based on regression analyses of the separate cost elements (i.e., engineering, tooling, manufacturing labor, manufacturing materials, flight testing, and quality control) for a sample of 25 military aircraft (including fighters, bombers, and transports). Method 2 is similar except that the regression is based on total airframe cost rather than on the summation of separate cost elements. Methods 3 and 4 are the same as 1 and 2, respectively, except that the data base in the regression analysis was restricted to large, subsonic aircraft (i.e., B-52, C-5, C-130, C-133, KC-135, and C-141). Note that significant differences exist among the estimates by the four methods for both the development and the production costs.

Engines. Three alternative methods are available for estimating engine production and development costs; these are also illustrated in Table D-1. Methods 1 and 2, the so-called time-of-arrival (TOA) models recently advanced by Nelson and Timson [89], express engine acquisition costs in terms of the following engine parameters:

- o Maximum turbine inlet temperature
- o Fan pressure ratio
- o Maximum dynamic pressure

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[a]Here, and in the following examples, we assume that 112 UE aircraft are procured. Thus, of the total number of aircraft produced (134), 5 are development aircraft and 17 are allotted for the depot-maintenance pipeline and for attrition replacement.

Table D-1

ILLUSTRATIVE ACQUISITION COSTS USING VARIOUS ESTIMATING RELATIONSHIPS

*** VERY LARGE AIRPLANE ACQUISITION COSTS *** 04/19/76

SYNTHETIC JP FUELED STRATEGIC AIRLIFTER (VLA-JP)
MINIMUM GROSS WEIGHT POINT DESIGN (FROM ASD)

* AIRPLANE CHARACTERISTICS USED FOR COSTING *

AIRFRAME:		ENGINES:		AVIONICS:
AMPR WEIGHT ---	634463. LBS	SLS THRUST -	89727. LBS	GUIDANCE
MAX. SPEED ----	475. KTS	SLS ETSFC --	0.269 /HR	NAVIGATION
MAX. DYN. P. --	630. PSF	T. I. T. ---	2500. D F	COMMUNICATION
MAX. MACH NO. -	0.800	E. P. R. ---	35.0	
IOC YEAR ------	1987	WEIGHT -----	12199. LBS	
NO. A/C PROD. -	134	DIAMETER ---	10.92 FT	
NO. DEV. A/C --	5	LENGTH -----	19.92 FT	
A/C PER YEAR --	12	CHEM. FUEL ---	JP	
NO. PRIOR A/C -	0	ENG. PER A/C -	6	

** SUMMARY OF ACQUISITION COSTS BY CATEGORY **
(FOLLOWING COSTS IN MILLIONS OF 1975 DOLLARS)

AIRFRAME:		DEVELOPMENT	PRODUCTION	TOTAL
	METHOD 1	2696.905	7096.191	9793.094
	METHOD 2	2458.142	6641.070	9099.211
	METHOD 3	3214.226	9872.188	13086.410
	METHOD 4	3529.777	9155.250	12685.023

ENGINES:		DEVELOPMENT	PRODUCTION	TOTAL
	METHOD 1	101.323	1612.469	1713.792
	METHOD 2	229.377	1735.427	1964.804
	METHOD 3	548.778	2218.940	2767.718

AVIONICS:		DEVELOPMENT	PRODUCTION	TOTAL
	METHOD 1	6.343	163.648	169.991

INITIAL SPARES:		DEVELOPMENT	PRODUCTION	TOTAL
	METHOD 1	428.601	1741.898	2170.499
	METHOD 2	207.418	1348.280	1555.698
	METHOD 3	337.894	1919.943	2257.837

- o Specific fuel consumption (sea level static)
- o Maximum thrust (sea level static)
- o Engine weight
- o Engine volume
- o Allotted development time
- o Production quantity and rate
- o Year of model qualification test (MQT)

The first six of the parameters are also the independent variables in regression equations that predict the expected time of arrival of the engine under consideration. This expected time of arrival is the year in which the engine might pass the model qualification test if technology developments followed historical trends. The calculated time-of-arrival term then appears as an independent variable in the cost-estimating relationships. A predicted time of arrival that is substantially later than the input year for the model qualification test (i.e., the year that the engine is required by the aircraft development program) will increase both the development and production costs of the engine.[a] In other words, such circumstances suggest that the engines represent a more significant advance in technology than can be anticipated from historical trends.

The Method 1 time-of-arrival model was derived from a data base consisting of 26 military turbojet and turbofan engines (i.e., TOA26 [89]). Method 2's base included 11 additional commercial turbojets and turbofans (i.e., TOA37 [89]). The engine cost by Method 3, shown in Table D-1, were estimated with a less complex model. In this case, the regression analysis yields acquisition costs in terms of maximum thrust, engine volume, development time, production rate, and production quantity (i.e., the "Standard Model" [89]). Again, a

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[a]For the VLA-JP, we have assumed an initial operational capability (IOC) of 1987. Assumed IOC for the cryogenic-fueled airplanes was also 1987, but 1992 for the nuclear airplanes.

significant variation in the engine acquisition costs estimated by the three methods can be observed.[a]

Avionics. Table D-2 presents the actual average costs of avionics incurred for the final buy of 23 C-5A aircraft. We have assumed that

Table D-2

C-5A AVIONICS COSTS
(Thousands of 1973 dollars)

Item	Cost per Aircraft
Guidance	
AFCS	111.0
Flight direction computer	25.6
Astro inertial doppler IDNE	377.0
AHRU compass	45.9
Navigation	
Multimode radar	247.0
ADF	4.2
Loran	33.8
Tacan	64.8
Radar altimeter	29.4
Glidescope	2.4
VOR/LOC	5.7
Radar beacon	13.8
Navigation selection panel	2.6
Communications	
HF/SSB	60.1
UHF	18.0
VHF/FM	4.5
VHF communication	6.1
MADAR	
Computer	42.9
OSC/read	33.6
Printout	6.0
Total	1134.4

[a]An input development time of six years coupled with the assumed IOC years causes the time-of-arrival models to regard these engines as representative of a relatively low technology. That is, the engine development costs in Table C-1 for Methods 1 and 2 are only meaningful if it is assumed that much of the advanced technology (e.g., a turbine inlet temperature of 2500°F) is well within the state of the art at the time these engines are developed. Compressing the development time would also cause a significant increase in development costs. For example, decreasing development time from 6 to 5 years could cause the models to estimate costs as much as 40 percent greater.

the average unit cost of avionics for the very large airplanes is the same as that for the C-5A. Each item listed in Table D-2 is included in each of the alternatives except for the MADAR (malfunction detection and recording) system; the MADAR unit is also not included in the C-5B. The costs shown in Table D-2 (as well as the airframe and engine cost-estimating relationships in the cited literature) are in constant 1973 dollars.

Indexes for expressing these costs in constant 1975 dollars are tabulated by category in Table D-3. The category "Other" gives the average of the airframe, engines, and avionics indexes for each year; it has been used to adjust the cost of the nuclear reactor system, initial spares, etc.

Table D-3

PRICE INDEXES BY AIRCRAFT COST CATEGORY

Year	Cost Category				
	Airframe	Engines	Avionics	Fuel	Other
1970	0.795	0.900	0.881	0.855	0.859
1971	0.841	0.939	0.922	0.881	0.900
1972	0.918	0.972	0.971	0.907	0.954
1973	1.000	1.000	1.000	0.933	1.000
1974	1.115	1.099	1.104	1.000	1.106
1975	1.227	1.179	1.206	1.065	1.204
1976	1.334	1.262	1.302	1.127	1.299
1977	1.436	1.343	1.395	1.186	1.391
1978	1.536	1.421	1.485	1.243	1.481
1979	1.635	1.499	1.574	1.300	1.569
1980	1.732	1.575	1.663	1.356	1.657
Post-1980 assumed annual rate %	4.6	3.2	4.2	3.2	3.9

SOURCE: USAF Aeronautical Systems Division [90].

<u>Nuclear System</u>. Cost estimates for the nuclear reactor system are similar to those recently developed by a study team at the Air Force Institute of Technology [10]. Their estimates of the nominal

development costs of the various elements of the nuclear (liquid-metal-cooled reactor) system are presented in Table D-4. We have made two cost estimates for each element of the nuclear system--a pessimistic (high) estimate and an optimistic (low) estimate. The high and low estimates for the development costs are those shown in Table D-4 plus or minus 500 million dollars, respectively [10].

Table D-4

NOMINAL DEVELOPMENT COST OF NUCLEAR SYSTEM
(Millions of 1974 dollars)

Element	Cost
Reactor and containment vessel	1400
Heat exchangers	20
Safety valves	25
Total	1445

SOURCE: Air Force Institute of Technology [10].

The cumulative production cost, C_n, of the reactor systems (in millions of 1974 dollars) for the number of production aircraft, Q_p, has been calculated by the following relationship [10].

$$C_n = \left\{\left(\frac{MWt}{475}\right)^{0.6} C_b + n_e[\log_e(C_{he}) + 0.35]Q_p^{-0.152}\right\}Q_p \qquad \text{(D-1)}$$

where

MWt - thermal output of the reactor (megawatts)

C_b - average unit cost of a 475-megawatt reactor (see Table D-5)

n_e - number of dual-mode engines per aircraft

C_{he} - average unit cost of the first 10 production heat exchangers (see Table D-5)

The low and high estimates for C_b and C_{he} are shown in Table D-5.

Table D-5

BASE ESTIMATES OF COST PARAMETERS IN EQUATION D-1
(Millions of 1974 dollars)

Parameter	Low	High
C_b	27.0	53.0
C_{he}	0.5	1.0

SOURCE: Air Force Institute of Technology [10].

The nuclear system cost estimates must be considered much less reliable than those of the airframe or the engines. This is inevitable since the system represents almost a wholly new technology. Despite this uncertainty, our discussions with experts in the nuclear reactor industry have indicated that our cost estimates appear reasonable.

Initial Spares and Other Equipment. The remaining elements of the system acquisition costs have been assimilated in this last category. Included are the following cost elements:

- Initial spares
- Aerospace ground equipment (AGE)
- Support equipment
- Training devices
- Data

We have estimated these costs by extrapolating the corresponding costs of the C-5A. Table D-6 displays the development and production costs for this category in terms of a fraction of the development and production costs of each of the previously discussed major cost categories. The fractions for the nuclear cost category are, of course, little more than a guess.

The absolute values of the cost estimates in this category should be regarded with caution. In a relative sense, however, we believe

Table D-6

COSTS OF INITIAL SPARES AND OTHER EQUIPMENT AS FRACTIONS OF MAJOR COSTS

Cost Category	Development	Production
Airframe	0.08	0.13
Engines	0.02	0.25
Avionics	0.01	0.50
Nuclear system	0.25	0.25

that they will not introduce any inconsistent biases when applied to the alternative airplanes examined in this study.

Synthesis of Acquisition Costs. The low, high, and nominal cost estimates for each of the aforementioned categories are summarized in Table D-7. Low and high estimates in each category are what the terms imply. The nominal estimate is the average of however many methods are shown for each category in Table D-1.[a]

Table D-7 also provides the acquisition cost total and the average unit flyaway cost.

Operating and Support Costs

O&S costs, apart from fuel, include the following:

- o Squadron personnel
- o Base operating support personnel
- o Medical personnel
- o Common AGE
- o Replenishment spares
- o Depot maintenance
- o System support
- o General support

[a]Table D-1 presents three methods for calculating the cost of initial spares, AGE, etc. These three methods correspond to application of the factors shown in Table D-6 to the low, high, and nominal estimates, respectively, for each category (other than initial spares, AGE, etc.) of Table D-7.

Table D-6

COSTS OF INITIAL SPARES AND OTHER EQUIPMENT AS FRACTIONS OF MAJOR COSTS

Cost Category	Development	Production
Airframe	0.08	0.13
Engines	0.02	0.25
Avionics	0.01	0.50
Nuclear system	0.25	0.25

that they will not introduce any inconsistent biases when applied to the alternative airplanes examined in this study.

Synthesis of Acquisition Costs. The low, high, and nominal cost estimates for each of the aforementioned categories are summarized in Table D-7. Low and high estimates in each category are what the terms imply. The nominal estimate is the average of however many methods are shown for each category in Table D-1.[a]

Table D-7 also provides the acquisition cost total and the average unit flyaway cost.

Operating and Support Costs

O&S costs, apart from fuel, include the following:

- o Squadron personnel
- o Base operating support personnel
- o Medical personnel
- o Common AGE
- o Replenishment spares
- o Depot maintenance
- o System support
- o General support

[a]Table D-1 presents three methods for calculating the cost of initial spares, AGE, etc. These three methods correspond to application of the factors shown in Table D-6 to the low, high, and nominal estimates, respectively, for each category (other than initial spares, AGE, etc.) of Table D-7.

Table D-7

ILLUSTRATIVE SUMMARY OF THE ACQUISITION COSTS

*** VERY LARGE AIRPLANE ACQUISITION COSTS *** 04/19/76

SYNTHETIC JP FUELED STRATEGIC AIRLIFTER (VLA-JP)
MINIMUM GROSS WEIGHT POINT DESIGN (FROM ASD)

* AIRPLANE CHARACTERISTICS USED FOR COSTING *

AIRFRAME:		ENGINES:		AVIONICS:
AMPR WEIGHT ---	634463. LBS	SLS THRUST -	89727. LBS	GUIDANCE
MAX. SPEED ----	475. KTS	SLS ETSFC --	0.269 /HR	NAVIGATION
MAX. DYN. P. --	630. PSF	T. I. T. ---	2500. D F	COMMUNICATION
MAX. MACH NO. -	0.800	E. P. R. ---	35.0	
IOC YEAR ------	1987	WEIGHT -----	12199. LBS	
NO. A/C PROD. -	134	DIAMETER ---	10.92 FT	
NO. DEV. A/C --	5	LENGTH -----	19.92 FT	
A/C PER YEAR --	12	CHEM. FUEL ---	JP	
NO. PRIOR A/C -	0	ENG. PER A/C -	6	

* TOTAL ACQUISITION COSTS *
(FOLLOWING COSTS IN MILLIONS OF 1975 DOLLARS)

	LOW	HIGH	NOMINAL
PRODUCTION:			
AIRFRAME:	6641.1	9872.2	8191.2
ENGINES:	1612.5	2218.9	1855.6
AVIONICS:	163.6	163.6	163.6
FLYAWAY TOTAL:	8417.2	12254.8	10210.4
INITIAL SPARES:	1348.3	1919.9	1670.0
PROCUREMENT TOTAL:	9765.5	14174.7	11880.5
DEVELOPMENT:			
AIRFRAME:	2458.1	3529.8	2974.8
ENGINES:	101.3	548.8	293.2
AVIONICS:	6.3	6.3	6.3
INITIAL SPARES:	207.4	428.6	324.6
RDT&E TOTAL:	2773.2	4513.5	3598.9
* ACQUISITION TOTAL:	12538.7	18688.2	15479.4 *
UNIT FLYAWAY COST:	65.249	94.998	79.151

Our approach to these costs is much less sophisticated than that to acquisition costs. We have divided O&S costs into fixed components (i.e., independent of peacetime flying activity) and variable components. Both categories (excluding fuel costs) have been estimated by a straightforward extrapolation of recent Air Force experience with the C-130E, C-141A, and C-5A aircraft.[a]

Fixed O&S Costs. Two methods have been used to estimate the fixed O&S costs. The first, based on aircraft AMPR weight, is given by

$$c_F = 350{,}000 + 3.55W_A + 11{,}360(2N_O + N_E)R \qquad \text{D-2)}$$

where

c_F - annual fixed cost per UE aircraft (1974 dollars)
W_A - aircraft AMPR weight (lb)
R - flight crew ratio
N_O - number of officers in flight crew
N_E - number of enlisted men in flight crew

The last term in Equation D-2 represents the flight crew costs; the first and second, the other fixed costs.

The second method was derived on the basis of average unit flyaway cost. The relationship in this case is

$$c_F = 600{,}000 + 0.0194c_u + 11{,}360(2N_O + N_E)R \qquad \text{(D-3)}$$

where

c_u - average unit flyaway cost (1974 dollars)

Estimates of the fixed O&S costs for the VLA-JP for both methods are illustrated in Table D-8. The 1974 dollars have been converted to 1975 dollars using the "Other" category in Table D-3. Note that the costs shown in Table D-8 are the annual costs per 16 UE squadron.

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[a]We are grateful to Joseph P. Large of Rand for developing these estimating relationships for nonfuel operating and support costs.

Table D-8

ILLUSTRATIVE OPERATING AND SUPPORT COSTS
FOR THE VLA-JP AIRCRAFT

*** VERY LARGE AIRPLANE ANNUAL OPERATING COSTS *** 04/19/76

SYNTHETIC JP FUELED STRATEGIC AIRLIFTER (VLA-JP)
MINIMUM GROSS WEIGHT POINT DESIGN (FROM ASD)

* PARAMETERS USED FOR COSTING *

OPERATIONAL:		FUEL:	
NO. OF SQUADRONS ----	7	PRIMARY SYSTEM -----	JP
UE A/C PER SQUADRON -	16	FUEL CONSUMPTION -	712. MMBTU/HR
CREWS PER UE A/C ----	4.0	FUEL CONSUMPTION -	38258. LBS/HR
FLIGHT CREW MAKE-UP		AVG. FUEL COSTS --	3.01 $/MMBTU
OFFICERS -------	3		
ENLISTED MEN ---	3		
FH PER A/C PER MO. --	60		

** ANNUAL COSTS PER SQUADRON (MILLIONS OF 1975 DOLLARS) **

FIXED:		CREW	OTHER	TOTAL
	METHOD 1	7.881	50.132	58.012
	METHOD 2	7.881	36.127	44.007

VARIABLE:		FUEL	OTHER	TOTAL
	METHOD 1	26.279	47.740	74.019
	METHOD 2	26.279	32.535	58.814

** TOTAL OPERATING COSTS FOR ALL SQUADRONS **

CATEGORY:	LOW	HIGH	NOMINAL
FIXED:	306.052	406.085	357.068
VARIABLE:	411.696	518.132	464.914
* ANNUAL TOTAL:	719.748	924.218	821.983 *

** PARAMETERIZATION OF NOMINAL COSTS (ALL SQUADRONS) **

FH/MO/AC	FIXED	FUEL	OTHER VAR.	TOTAL
0.	357.068	0.0	0.0	357.068
30.	357.068	91.975	140.482	589.525
60.	357.068	183.951	280.963	821.982
90.	357.068	275.926	421.445	1054.440
120.	357.068	367.902	561.927	1286.897
150.	357.068	459.877	702.409	1519.355
180.	357.068	551.853	842.891	1751.812
210.	357.068	643.828	983.373	1984.269
240.	357.068	735.804	1123.854	2216.727
270.	357.068	827.779	1264.336	2449.184
300.	357.068	919.755	1404.818	2681.642

Variable O&S Costs. The fuel component of these costs has been calculated by assuming that the average peacetime fuel consumption per hour is approximately the same as the fuel consumption per hour when flying the design radius mission profile. The following equation pertains

$$c_f = U_f\, f_c\,(12\ \mathrm{FH}) \qquad \text{(D-4)}$$

where

c_f - annual fuel cost per UE aircraft (\$)

U_f - average unit fuel cost (\$/MMBtu)

f_c - average fuel consumption per hour (MMBtu/hr)—design radius mission

FH - average peacetime flying hours per month

Average unit fuel costs and fuel consumption rates for the alternatives are presented in Table D-9. The fuel consumption for the nuclear

Table D-9

FACTORS FOR CALCULATING ANNUAL FUEL COST

Alternative	Fuel	Unit Cost (1975\$ /MMBtu)	Fuel Consumption Rate (MMBtu/hr)
VLA-JP	JP	3.21	712
VLA-LCH_4	LCH_4	4.28	759
VLA-LH_2	LH_2	9.78	628
VLA-NUC	JP	3.21	314
	nuclear	0.65	1812
VLA-LH_2*	LH_2	9.78	785
VLA-NUC*	JP	3.21	231
	nuclear	0.65	1319
C-5B	JP	3.21	466

SOURCE: Appendixes A and E and Ref. 19.

airplanes are the averages for each mode of operation--JP and nuclear. (In Section VIII, certain mission profiles for the nuclear airplane involved a proportionately greater fraction of the total flight time in the nuclear mode. Where this was so, average fuel consumptions were appropriately adjusted.)

Two methods have also been employed to estimate the other variable operating costs. The first can be expressed as,

$$c_V = 0.005425W_A \tag{D-5}$$

where

c_V - average cost per flying hour per UE (1974 dollars)

and the second by

$$c_V = 150 + 0.0000334c_u \tag{D-6}$$

Table D-8 also provides an example of the VLA-JP's variable costs for both methods.

Synthesis of O&S Costs. Low, high, and nominal estimates of O&S costs have been determined in a fashion analogous to that used in determining acquisition costs. Table D-8 gives them for the VLA-JP. Once again, a fairly substantial difference exists between the low and high estimate for both categories.

Table D-8 also presents results that indicate how the O&S costs vary with changes in the peacetime utilization rate. For example, doubling the flying hours per month per UE from 60 to 120 causes only about a 57 percent increase in total O&S costs.

Also observe that fuel costs represent about 22 percent of the total nominal O&S costs of the VLA-JP for a 60-hour per month UTE rate.

Life-Cycle Cost Model

The cost estimating techniques described above have been incorporated into a life-cycle cost computer model developed specifically for the present study. Indeed, Tables D-1, D-7, and D-8 are printed output from this model.

Life-cycle costs have been determined by apportioning the required expenditures for RDT&E, acquisition, and O&S by fiscal year over the total life of the system. Thus, required inputs include the assumed development times and production rates as well as the desired IOC year. Table D-10 illustrates this allocation for a fleet of 112 UE VLA-JP (seven squadrons).[a]

In addition to giving costs in constant 1975 dollars, Table D-10 presents them in terms of budget (or then-year) dollars. Budget dollars were calculated with inflators based on the cost indexes presented in Table D-3. The effect of discounting both constant and budget dollars is also shown in Table D-10 for a 10 percent discount rate.

Observe that the base year in the discounting scheme is the initial operational capability year. Dollars expended before the IOC year are thus valued more highly than those spent afterwards. Such an approach to discounting was necessary since later IOCs (1992 versus 1987) were assumed for the nuclear airplanes. With this approach, meaningful comparisons of discounted costs can be made among all alternatives.

Finally, cumulative expenditures by fiscal year (corresponding to the annual expenditures of Table D-10) are listed in Table D-11. Note the very significant effect the relatively high annual inflation factors --an average of 6.8 percent through 1980 and 4.3 percent thereafter-- have on the total life-cycle cost expressed in budget dollars.[b]

---

[a]The allocation of RDT&E costs assumed that the development costs were equally spread over the input development time. We also assumed a constant production rate and a constant allocation of production costs over the production period. (Although a constant production rate may be unrealistic, the expenditures should be close to being equally divided among the years of the production run.) Operating and support were determined by the number of operational squadrons in each fiscal year. We interpreted a 20-year life cycle for seven squadrons as being equivalent to 140 operational squadron-years.

[b]We apologize to the reader for the printout's occasionally giving eight digits. Obviously, we do not intend to suggest that the cost estimates have that degree of accuracy.

Table D-10

ILLUSTRATIVE EXPENDITURES BY FISCAL YEAR FOR THE VLA-JP AIRCRAFT

*** VERY LARGE AIRPLANE LIFE CYCLE COSTS *** 04/19/76

SYNTHETIC JP FUELED STRATEGIC AIRLIFTER (VLA-JP)
MINIMUM GROSS WEIGHT POINT DESIGN (FROM ASD)

* PARAMETERS USED FOR LIFE CYCLE COSTING *

DEVELOPMENT TIMES:
AIRFRAME ------- 7.5 YEARS
ENGINES -------- 6.0 YEARS
AVIONICS ------- 4.0 YEARS
SPARES, ETC. --- 4.0 YEARS
LIFE CYCLE LENGTH - 20.0 YEARS

MISSION BASIS:
DESIGN PAYLOAD --- 175.0 TONS
DESIGN RANGE ----- 6400. N. MI.
DESIGN RADIUS ---- 3600. N. MI.
TOTAL UE AIRCRAFT ----- 112
DISCOUNT FACTOR ------- 0.100

** LIFE CYCLE COSTS BY FISCAL YEAR (MILLIONS OF DOLLARS) **

FISCAL YEAR	ACTIVE SQUADRONS	1975 DOLLARS	BUDGET DOLLARS	DISCOUNTED 1975 DOL.	DISCOUNTED BUDG. DOL.
77	0	260.098	304.401	674.621	789.531
78	0	404.245	505.693	953.181	1192.388
79	0	445.494	590.644	954.950	1266.088
80	0	458.382	642.887	893.252	1252.798
81	0	528.239	772.045	935.803	1367.718
82	0	528.239	806.549	850.730	1298.949
83	0	528.239	842.611	773.392	1233.663
84	0	608.714	1012.636	810.196	1347.815
85	0	1044.895	1805.896	1264.321	2185.131
86	0	1044.895	1885.286	1149.384	2073.813
87	1	1162.321	2174.891	1162.321	2174.891
88	1	1216.848	2369.084	1106.226	2153.714
89	2	1279.747	2590.969	1057.643	2141.298
90	3	1388.802	2917.439	1043.429	2191.918
91	3	1443.330	3153.717	985.815	2154.035
92	4	1514.599	3439.523	940.449	2135.678
93	5	1615.283	3807.632	911.788	2149.315
94	5	1669.810	4093.366	856.879	2100.551
95	6	1749.451	4455.297	816.135	2078.437
96	7	1020.337	2588.450	432.724	1097.760
97	7	821.982	2107.530	316.911	812.548
98	7	821.982	2188.419	288.101	767.031
99	7	821.982	2272.431	261.910	724.071
0	7	821.982	2359.686	238.100	683.521
1	7	821.982	2450.309	216.455	645.247
2	7	821.982	2544.432	196.777	609.121
3	7	821.982	2642.190	178.889	575.021
4	7	821.982	2743.723	162.626	542.835
5	7	821.982	2849.180	147.842	512.454
6	7	821.982	2958.711	134.402	483.777
7	7	821.982	3072.475	122.184	456.708
8	7	821.982	3190.637	111.076	431.156
9--11	7	2142.853	8922.934	243.427	1011.491

Table D-11

ILLUSTRATIVE CUMULATIVE EXPENDITURES BY FISCAL YEAR FOR THE VLA-JP AIRCRAFT

*** VERY LARGE AIRPLANE LIFE CYCLE COSTS ***   04/19/76

SYNTHETIC JP FUELED STRATEGIC AIRLIFTER (VLA-JP)
MINIMUM GROSS WEIGHT POINT DESIGN (FROM ASD)

** CUMULATIVE LIFE CYCLE COSTS (MILLIONS OF DOLLARS) **

FISCAL YEAR	ACTIVE SQUADRONS	1975 DOLLARS	BUDGET DOLLARS	DISCOUNTED 1975 DOL.	DISCOUNTED BUDG. DOL.
77	0	260.098	304.401	674.621	789.531
78	0	664.343	810.094	1627.802	1981.919
79	0	1109.837	1400.737	2582.752	3248.008
80	0	1568.219	2043.625	3476.004	4500.805
81	0	2096.458	2815.669	4411.805	5868.520
82	0	2624.697	3622.218	5262.535	7167.469
83	0	3152.936	4464.828	6035.926	8401.129
84	0	3761.650	5477.461	6846.121	9748.941
85	0	4806.543	7283.355	8110.441	11934.070
86	0	5851.438	9168.641	9259.824	14007.883
87	1	7013.758	11343.531	10422.145	16182.773
88	1	8230.605	13712.613	11528.367	18336.484
89	2	9510.352	16303.578	12586.008	20477.781
90	3	10899.152	19221.016	13629.434	22669.699
91	3	12342.480	22374.730	14615.246	24823.734
92	4	13857.078	25814.254	15555.691	26959.410
93	5	15472.359	29621.883	16467.477	29108.723
94	5	17142.168	33715.246	17324.355	31209.273
95	6	18891.617	38170.543	18140.488	33287.707
96	7	19911.953	40758.992	18573.211	34385.465
97	7	20733.934	42866.520	18890.121	35198.012
98	7	21555.914	45054.938	19178.219	35965.043
99	7	22377.895	47327.367	19440.129	36689.113
0	7	23199.875	49687.051	19678.227	37372.633
1	7	24021.855	52137.359	19894.680	38017.879
2	7	24843.836	54681.789	20091.457	38627.000
3	7	25665.816	57323.977	20270.344	39202.020
4	7	26487.797	60067.699	20432.969	39744.852
5	7	27309.777	62916.879	20580.809	40257.305
6	7	28131.758	65875.563	20715.207	40741.078
7	7	28953.738	68948.000	20837.387	41197.785
8	7	29775.719	72138.625	20948.461	41628.941
9	7	30597.699	75451.938	21049.438	42035.977
10	7	31419.680	78892.750	21141.234	42420.246
11	4	31918.566	81061.438	21191.883	42640.426

****
* 20 YEAR TOTAL: 31918.566   81061.438   21191.883   42640.426 *
****

SUPPLEMENTARY COST RESULTS

Supplemental cost information for each of the seven alternative airplanes is next presented. For each airplane, we show

- o High, low, and nominal acquisition-cost estimates, in terms of the number of UE aircraft procured
- o 20-year O&S-cost estimates, in terms of the number of UE aircraft procured for average peacetime utilization rates of 2, 4, and 10 flying hours per day.

Unless otherwise noted, our assumptions (for example, about the number of UE per squadron) are those of the previously discussed example for the VLA-JP.

These data, together with the information presented above and in Section V, are sufficient for estimating the costs of any assumed VLA force size and/or peacetime flying schedule.

Design-Point Very Large Airplanes

Figure D-1a presents the supplemental acquisition cost information for the VLA-JP; corresponding information on 20-year O&S costs are shown in Fig. D-1b. Consider the O&S costs for 100 UE aircraft; these are about 14.5 billion dollars at 2 hours per day, and approximately 48 billion dollars at 10 hours per day. Thus, a fivefold increase in UTE rate causes only a little more than the tripling of O&S costs. Given that the relationships used to estimate the nonfuel O&S costs are based on USAF data (with relatively low average UTE rates), the estimates at the larger UTE rates should be regarded with caution.

Figures D-2 and D-3 present similar cost results for the VLA-LCH_4 and VLA-LH_2 aircraft, respectively. Observe that the O&S costs for both of these cryogenic-fueled airplanes are always substantially larger than those of the VLA-JP for any given number of UE aircraft. As noted earlier, however, the acquisition costs of the VLA-LH_2 are considerably smaller than the VLA-JP's--but not enough to offset its O&S cost disadvantage.

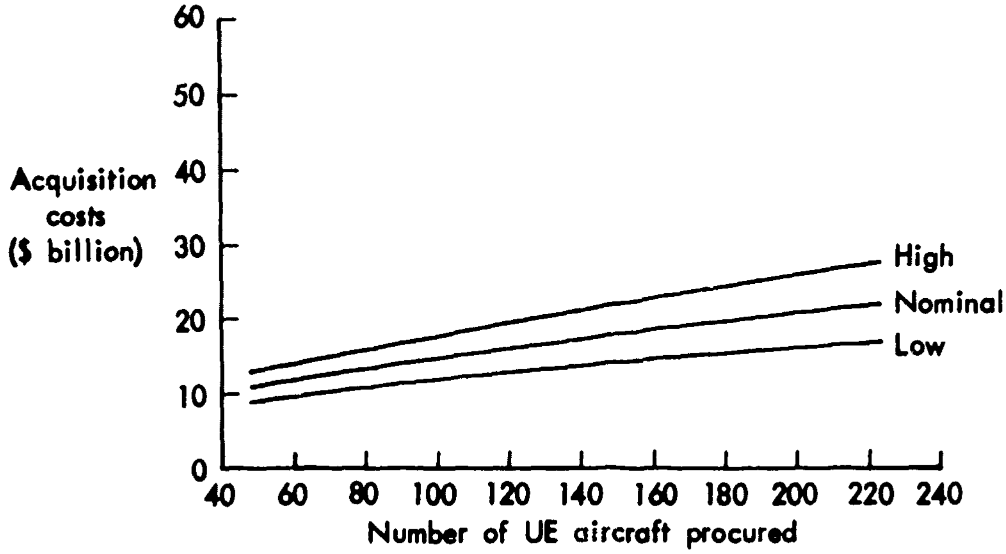

Fig. D-1a—VLA-JP acquisition-cost estimates

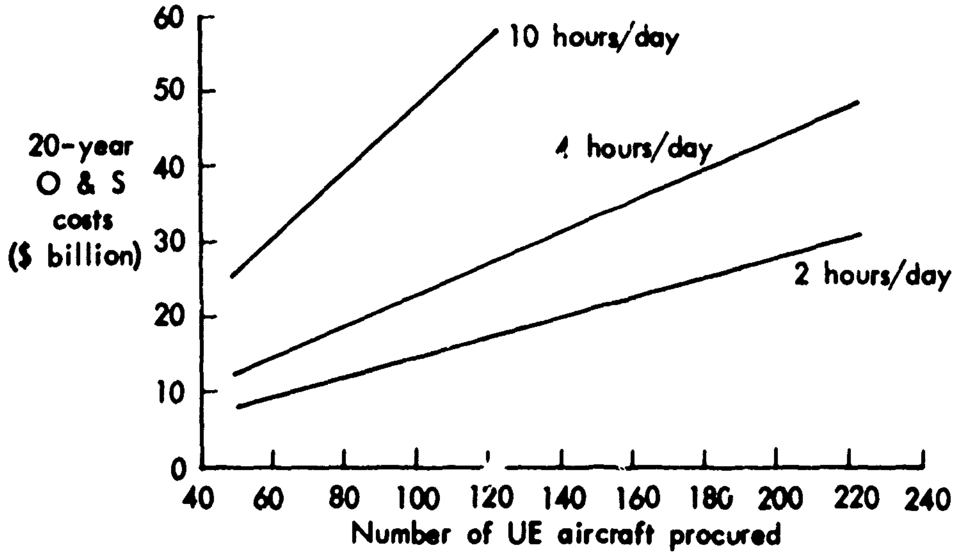

Fig. D-1b—VLA-JP 20-year O & S-cost estimates

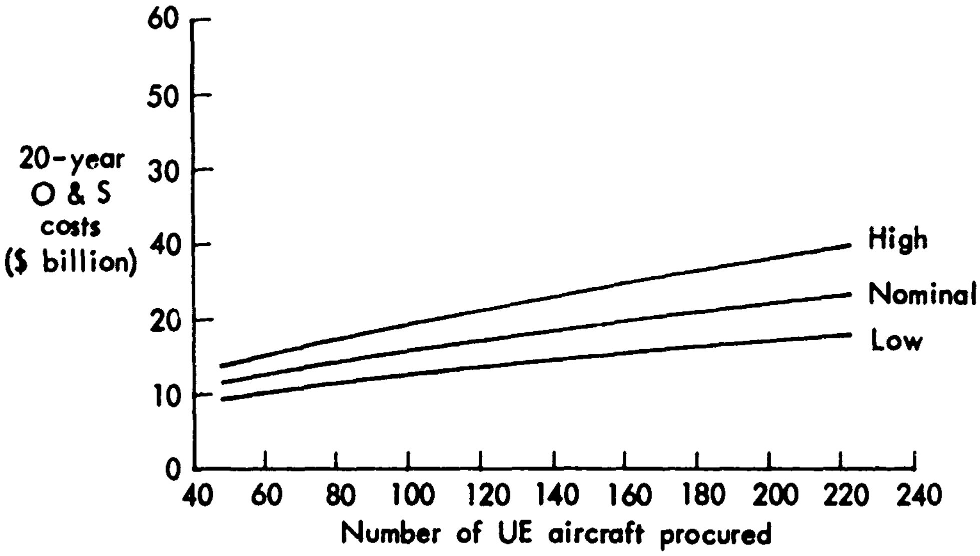

Fig. D-2a—VLA-LCH_4 acquisition-cost estimates

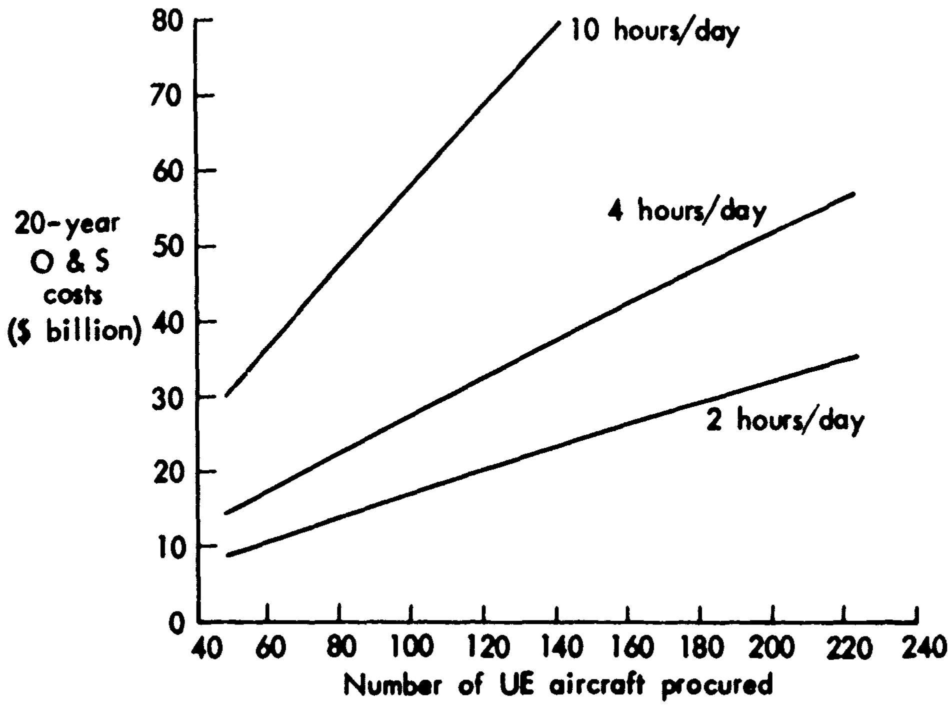

Fig. D-2b—VLA-LCH_4 20-year O & S-cost estimates

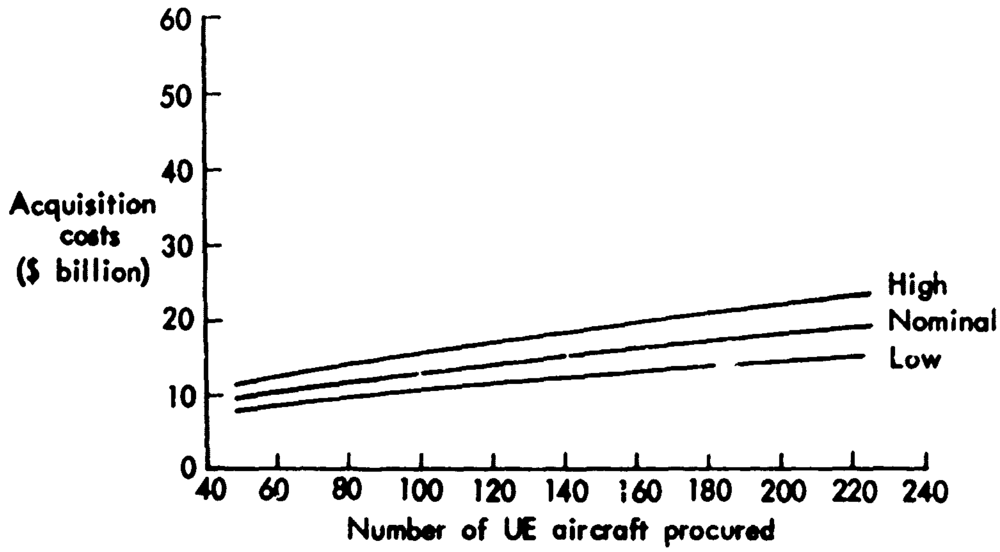

Fig. D-3a—VLA-LH_2 acquisition-cost estimates

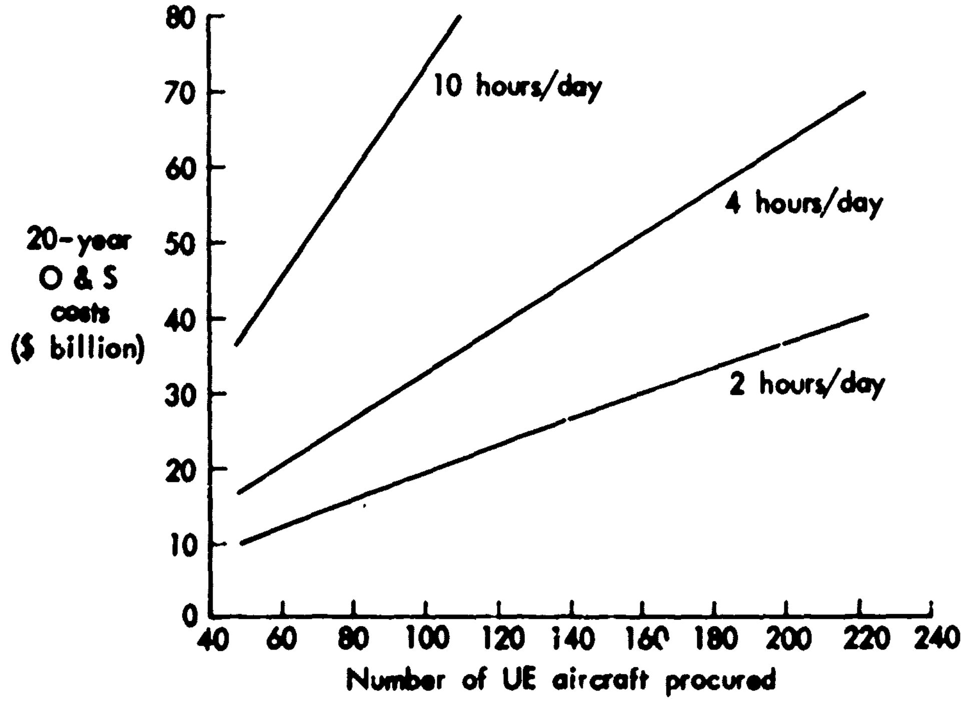

Fig. D-3b—VLA-LH_2 20-year O & S-cost estimates

The acquisition costs for the VLA-NUC are shown in Fig. D-4a. Two important observations are: (1) No matter what the number of UE aircraft, the VLA-NUC costs much more to acquire than any of the chemical-fueled airplanes. (2) The spread between the low and high estimates of the VLA-NUC's acquisition cost is significantly greater than for the other alternatives. Interestingly, the low estimate for the VLA-NUC is always slightly larger than the high estimate for the VLA-JP.

Figure D-4b displays the VLA-NUC's O&S costs. These are of the same magnitude as the VLA-LH_2 but, again, are very much larger than those of the VLA-JP.

Excursion-Case Aircraft

Supplemental cost estimates for the C-5B are presented in Fig. D-5. For any number of UE, the C-5B's acquisition costs and O&S costs are markedly smaller than those of any of the VLA alternatives. Of course, the capability of a single C-5B is also inferior to any of the very large airplanes. (See Sections IV, VII, and VIII.)

Using the described methodology for costing the C-5B (since it has been preceded by the C-5A) required that some of the input assumptions be modified. For example, we assumed that only two development aircraft would be required (versus five for each of the VLA alternatives). Production costs are even more troublesome; here, we have assumed that the first C-5B corresponded to the 31st C-5 production model. A total of 81 C-5As were built, but since the production line has been shut down it is obviously inappropriate to assume, for costing purposes, that the first C-5B is the 82d production article. On the other hand, the first C-5B could hardly be compared to the first C-5A in terms of production costs. What limited data are available on how restarting a closed production line affects the learning curve suggests that a slide backwards of about 50 production aircraft is reasonable. For the O&S costs, no special credit has been taken for any of the existing C-5A support equipment and facilities.

Finally, the supplemental costs for the VLA-LH_2* and VLA-NUC* are presented in Figs. D-6 and D-7, respectively. The reader is again

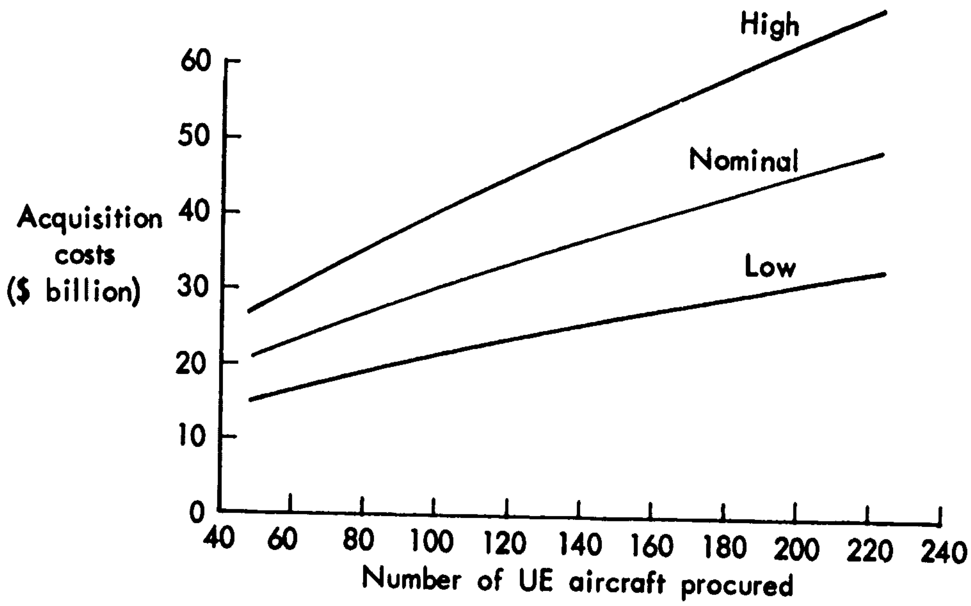

Fig. D-4a—VLA-NUC acquisition-cost estimates

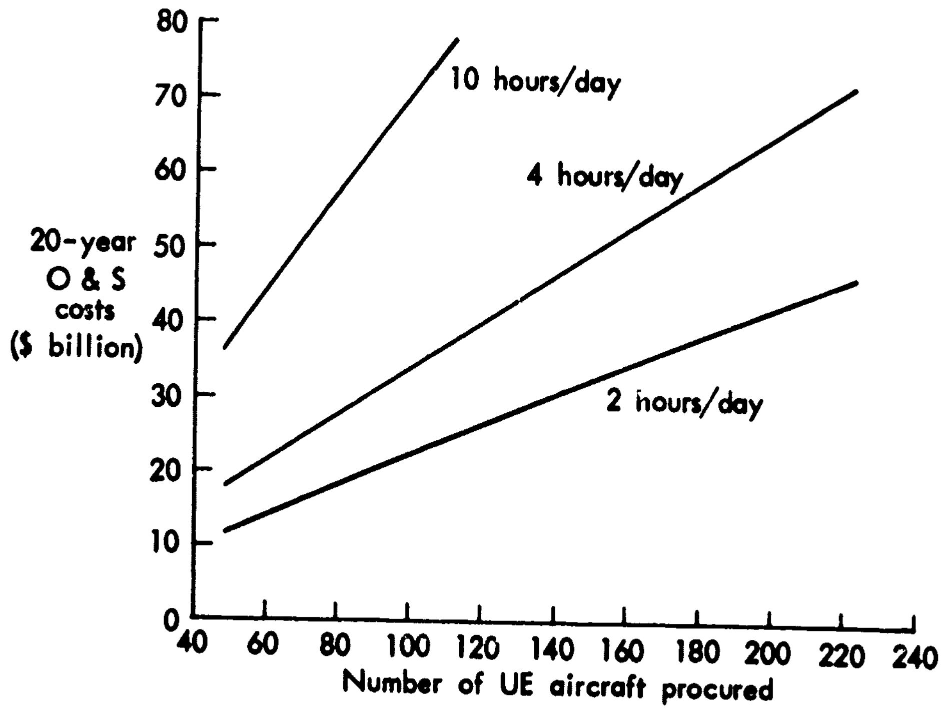

Fig. D-4b—VLA-NUC 20-year O & C-cost estimates

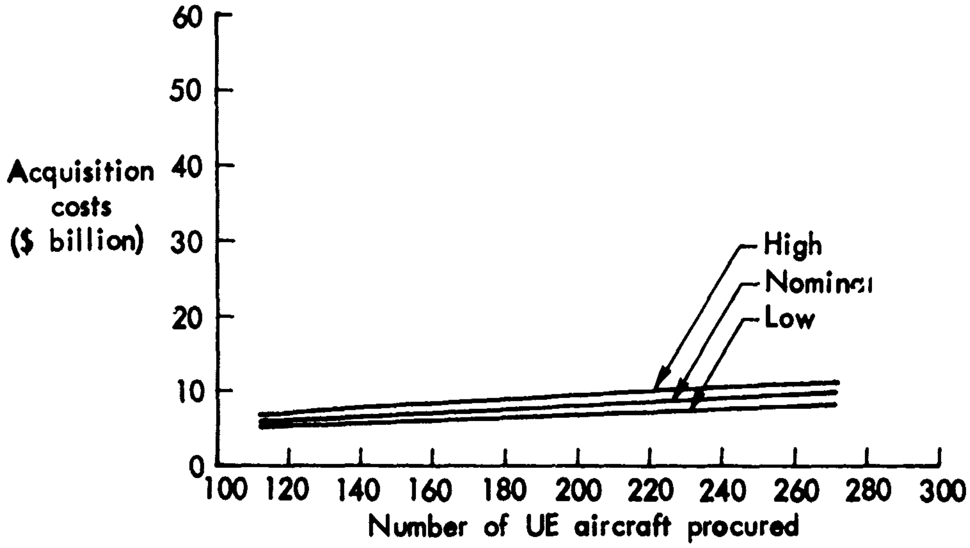

Fig. D-5a—C-5B acquisition-cost estimates

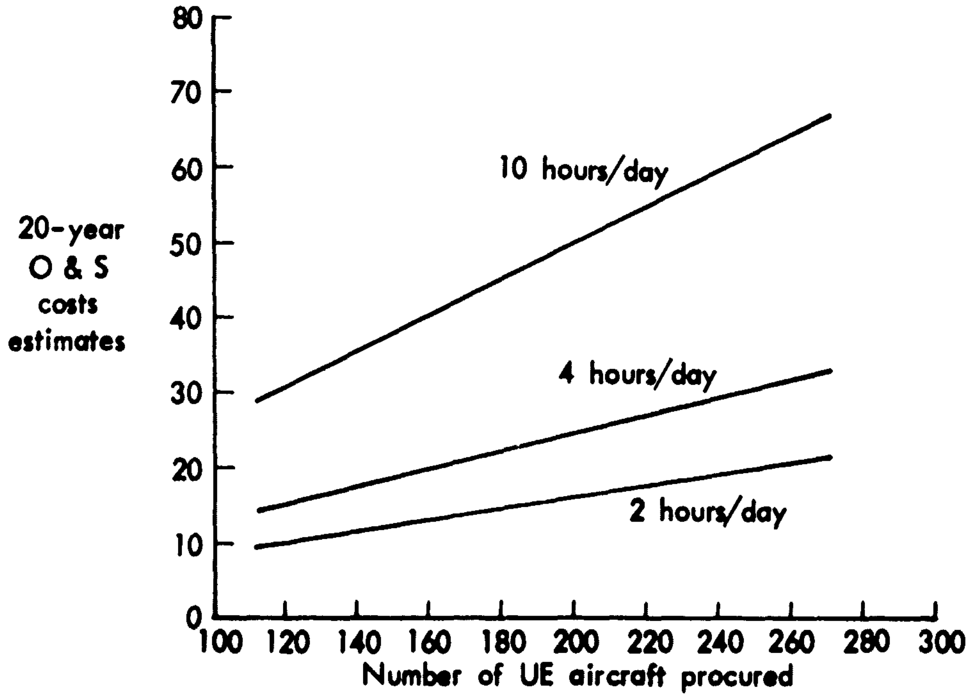

Fig. D-5b—C-5B 20-year O & S-cost estimates

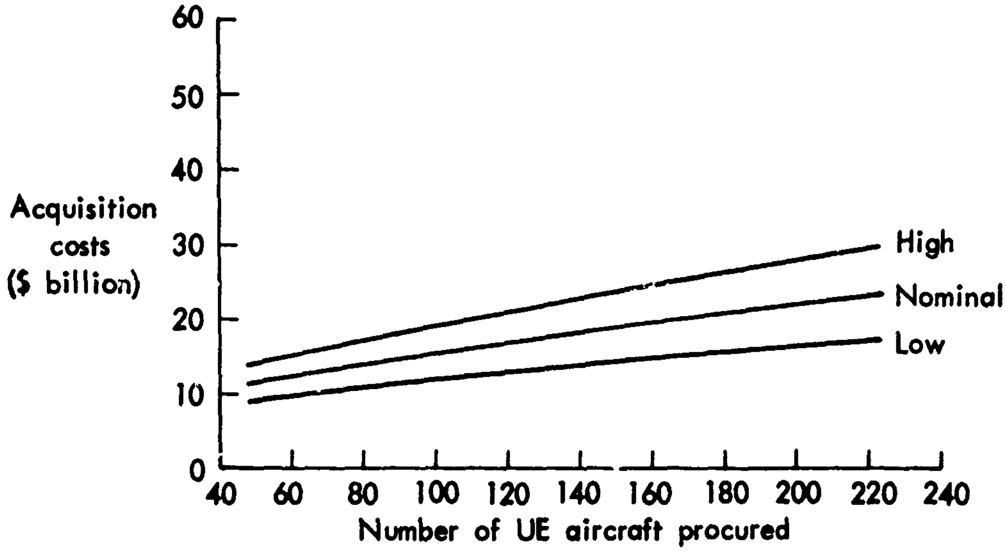

Fig. D-6a—VLA-LH$_2$* acquisition-cost estimates

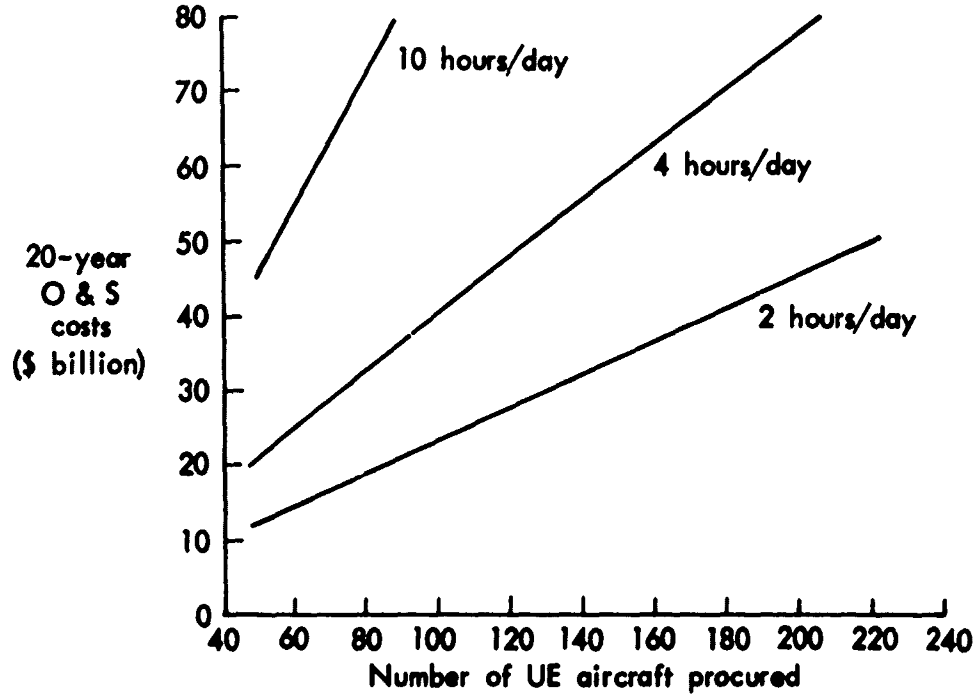

Fig. D-6b—VLA-LH$_2$* 20-year O & S-cost estimates

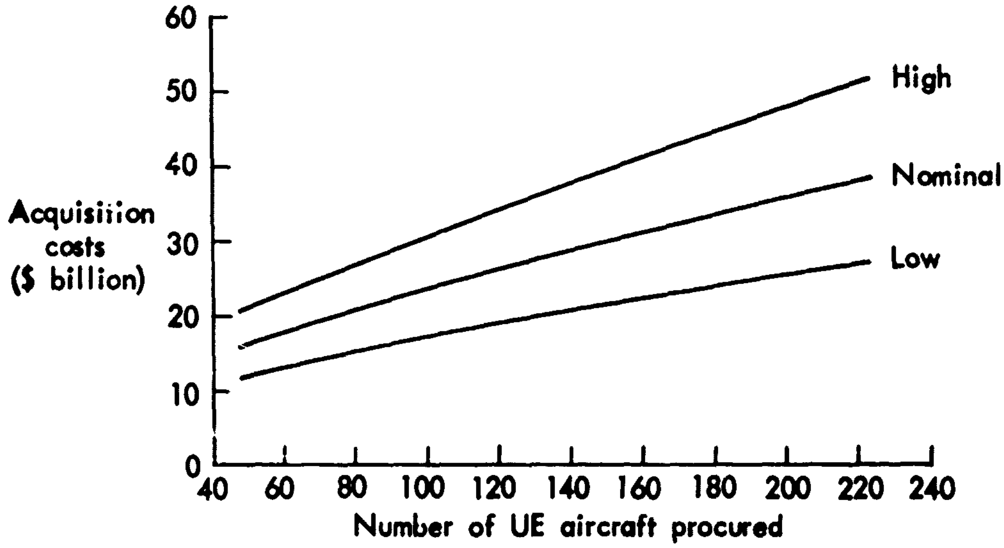

Fig. D-7a — VLA-NUC* acquisition-cost estimates

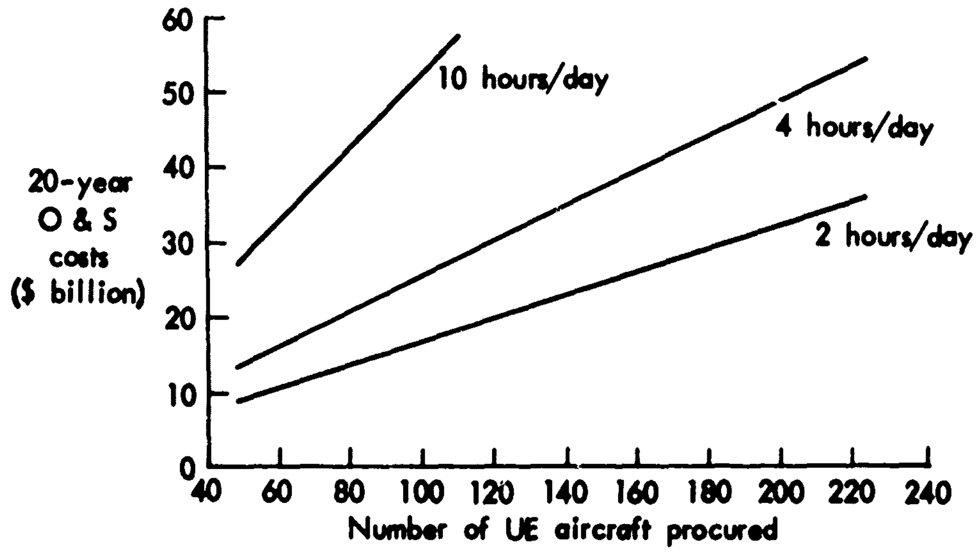

Fig. D-7b — VLA-NUC* 20-year O & S-cost estimates

cautioned, because of the variation in unit capability, not to compare these costs on a UE aircraft basis with the design-point alternatives.

ASD LIFE-CYCLE COST ESTIMATES

As part of their design analysis, ASD developed independent estimates of the life-cycle costs for each of the very large airplanes. Of course, some elements of the ASD methodology (e.g., unit fuel costs) were identical to the previously described analysis.

ASD developed separate estimates for RDT&E, production, and operating and support costs as described below. The costs of special facilities were included in those cases in which a need was demonstrated. Life-cycle costs were prepared for two levels of peacetime flying activity--720 and 1080 flying hours per year (i.e., about 2 and 3 flying hours per day).

Development Costs (RDT&E)

Airframes. Development costs for airframes were estimated using an earlier methodology developed by Rand (DAPCA II) [91]. The estimating equations for heavy-weight, low-speed aircraft were thought to be the most appropriate for the present effort. Five equations were used in estimating costs for the following areas: engineering, manufacturing labor, manufacturing material, tooling, and flight-test operations. Development costs were generated by assuming that five flight-test aircraft are required for each design. It was also assumed that none of the test vehicles would be transferred into the operating-aircraft inventory. The costs for test vehicles were generated in the same way as production costs for operating aircraft; the test vehicles are the first five units off the production line.

Engines. Development costs for the chemical-fueled engines were estimated with a "technology parameters" model also developed by Nelson and Timson [89].[a] Independent variables for this model are

[a]The technology parameters model is distinct from Nelson and Timson's three engine-cost models described earlier in this appendix.

the maximum thrust, engine weight, and development time. A 5 percent complexity factor was applied for the liquid-hydrogen and methane engines. Development costs for the nuclear propulsion system include both the engine and the nuclear reactor system. These costs were estimated on the basis of the latest available technical/cost data. The development cost for the nuclear system includes costs (possibly as high as 50 percent) that could be borne by the Energy Research and Development Administration, but for purposes of this study, these costs were treated as an Air Force responsibility.

Development costs for all aircraft under study include the cost of engines for the five test vehicles. These costs were generated in the same manner as the production costs, to be discussed later, and are assumed to be the first units manufactured.

Avionics. Avionics development costs were estimated on the basis of the minimum amounts necessary to adapt commercial avionics to the production vehicles.

Other. Not included thus far are the development costs of AGE, training equipment, or data; therefore, a factor of 13.1 percent was applied to the sum of the previously described development costs to account for these items.

Production Costs

Airframes. Production costs for airframes were also derived from the Rand DAPCA-II model. Five equations for heavy-weight, low-speed aircraft were used--again, for each of the following areas: engineering, manufacturing labor, manufacturing material, basic tooling, and flight-test operations. It was recognized that the aircraft under consideration were outside the data base of the model; however, an examination of the model indicated that the equations do take into consideration the complexities of large aircraft. Production costs for the nuclear systems included both reactor and containment vessel costs.

Engines. Production costs for engines using chemical fuels were developed using the following equation:

$$c_e = 1.321\ (T_{max})^{0.70}\ (Q_p)^{-0.152} \qquad \text{(D-7)}$$

where

c_e - average unit production cost (1972 dollars)

T_{max} - maximum sea-level static thrust (lb)

Q_p - production quantity

This equation was developed from cost quotations for high-thrust engines derived during a recent AMST (Advanced Medium STOL Transport) study and adjusted to meet the requirements of the engines for the VLAs. Nuclear engine costs were developed from the same data as those used for chemical engines, with the addition of the sodium potassium (NaK) radiator. This was accomplished by replacing the coefficient 1.321 in Equation D-7 with 1.723. Because these equations are based on 1972 dollars, escalation factors were applied to correct them to 1975 dollars.

Avionics. Avionics production costs were based on a recently completed ASD study of large aircraft (specifically, a study of the Advanced Tanker/Cargo Aircraft). The costs for an extremely austere avionics system were developed from data generated in that work. The study assumed that most components were available in existing commercial stocks, and this explains why all of the alternatives have relatively low avionics costs.

Other. A factor of 18.26 percent of flyaway cost was used for the costs of AGE, training, data, and initial spares. (Flyaway costs for the nuclear aircraft excluded nuclear systems costs.)

The existing cargo handling system was considered capable of providing adequate material handling for these aircraft. Costs were not developed for new manufacturing facilities, nor were specific costs generated for special airframe maintenance buildings that may be needed for base-level maintenance. The design of these aircraft enabled them to use runways presently capable of handling the C-5A,

747, DC-10, etc. Thus, no additional funds were allotted for runway or taxiway strengthening.

Operating and Support Costs (O&S)

Costs were generated for 20 years of operation on a typical military cargo-mission using an updated version of the PACE cost model [92]. Basic assumptions and a brief description of the methodology are described below.

Squadron size was assumed to be 16 UE aircraft with a total of seven squadrons. Manning for the primary program element, base operating support, and medical support is based on the current C-5A manning for a similar sized squadron. The flight crew for the chemical-fueled aircraft consisted of two pilots, one systems officer, and five airmen. An additional officer and airman were assumed for the nuclear aircraft. The training cost for these additional crewmen was estimated at $100,000 per officer and $60,000 per airman. This training cost was an external addition to the PACE model results.

The pounds of fuel consumed per flying hour (FH) were generated on the basis of the design-mission profile. Average unit fuel costs were the same as those shown in Table D-9. Nuclear aircraft fuel cost per flying hour consisted of a combination of JP cost plus the cost of nuclear fuel consumed.

Cost factors for base material support (BMS) per FH, replenishment spares per FH, and common AGE per UE per year were generated based on preliminary cost estimating relationships (CERs) developed by Hq USAF for large cargo aircraft. Recognizing that the specifications for the very large airplanes exceed the data base, additional factors were developed (except for BMS) based on the AMPR weight of the C-5A and the cost factors applicable to the C-5A. Actual costs using the C-5A data for the chemical-fueled aircraft ranged from 2 percent to 8 percent of the costs computed using the specifically developed CERs--thus supporting the use of these CERs. The differences were greater for nuclear aircraft as a result of the additional weight of the nuclear system, but the factors were kept constant to account for

system complexity. Factors used for Class IV mods (0.0038 of flyaway costs) and Class IV spares (0.075 of Class IV mods) were obtained from AFM 173-10 [92].

Summary

Table D-12 summarizes ASD's life-cycle cost estimates for the six very large airplane alternatives. A comparison of the ASD and Rand cost results (using identical assumptions regarding the number of aircraft acquired, etc.) is included as part of Section V.

Table D-12

SUMMARY OF ASD's LIFE-CYCLE COST ESTIMATES
(Billions of 1975 dollars)

Cost Element	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Development	4.1	4.5	2.9	7.6	4.5	5.7
Production	12.3	13.3	10.5	22.1	13.4	15.8
20-year operating and support						
- 720 flying hours per year	19.3	22.2	25.9	25.8	32.1	17.9
- 1080 flying hours per year	25.7	29.9	35.9	33.7	44.7	23.2
Total life cycle						
- 720 flying hours per year	35.7	40.0	39.2	55.5	50.0	39.4
- 1080 flying hours per year	42.1	47.7	49.3	63.4	62.6	44.7

NOTE: Based on the acquisition of 112 aircraft (i.e., no additional aircraft included for the depot-maintenance pipeline or attrition replacement).

Appendix E

COST AND ENERGY ASPECTS OF THE NUCLEAR FUEL CYCLE

Important concerns of the present study are the average unit costs and total energy implications of the fuel alternatives under consideration. These aspects of the three chemical fuels are discussed in detail in a separate report [19]; this appendix describes our companion analysis of nuclear fuel.

Understanding the cost and energy implications of nuclear power (for ground-based applications as well as airborne reactors) requires some background in what is commonly termed the "nuclear fuel cycle." We therefore begin with a general description of that cycle. There follows a discussion of the total energy requirements of the nuclear fuel supply process; the energy analysis is specific to the airborne liquid-metal reactor described in Appendix B. The appendix concludes with a presentation of our approach for estimating the average unit cost (dollars per million Btu) of the nuclear fuel.

DESCRIPTION OF THE FUEL CYCLE

The fuel cycle for the airborne liquid-metal-cooled reactor (ALMR) is qualitatively similar to that of the light-water reactor (LWR). (Nearly all commercial reactors in operation in the United States today are light-water reactors. We will describe the well-known fuel cycle for the LWR and note the differences that the ALMR would necessitate.)

There are essentially nine steps in the basic fuel cycle for commercial light-water reactors [93]. These are

- Mining
- Milling
- Conversion
- Enrichment
- Preparation

- o Fabrication
- o Fissioning in reactor
- o Reprocessing (and waste disposal)
- o Reconversion

Figure E-1 illustrates the placement of these steps in the cycle. The following discussion describes each step.

Mining and Milling

The mining step consists of extracting ores which contain uranium oxide, U_3O_8 (pitchblende); presently ore assays vary from 0.2 to 0.6 percent U_3O_8. The ore is further concentrated by mechanical and chemical milling methods to a high percentage of U_3O_8; at this stage it is called "yellow cake." The mills are usually located close to the mines, so that transportation costs and energy requirements are minimal.

The fissionable isotope, U^{235}, occurs naturally in very low concentrations, as shown in Fig. E-2 (p. 277). On the average, only 0.29 percent of the ore mined contains U_3O_8, of which 85 percent is natural uranium. Only 0.711 percent of the natural uranium is fissionable U^{235}. The remainder of the uranium consists of the nonfissionable uranium isotopes, U^{238} (99.2831%) and U^{234} (0.0058%).

Conversion

The enrichment plants are designed to process the gaseous compound, uranium hexafluoride (UF_6). What the conversion plant does is transform the yellow cake into this compound.

Enrichment

For sustained fission to occur, fissile material must be present in sufficient concentrations--the exact concentration depends on the nuclear reactor's design. Enrichment to the desired level occurs at three federally owned diffusion plants.[a] For LWRs, the uranium is

[a]Today all U.S. enrichment plants are of the gaseous diffusion type [94,95]. Advanced technology enrichment plants, using the centrifuge concept, promise reduced enrichment costs and energy requirements [96,97].

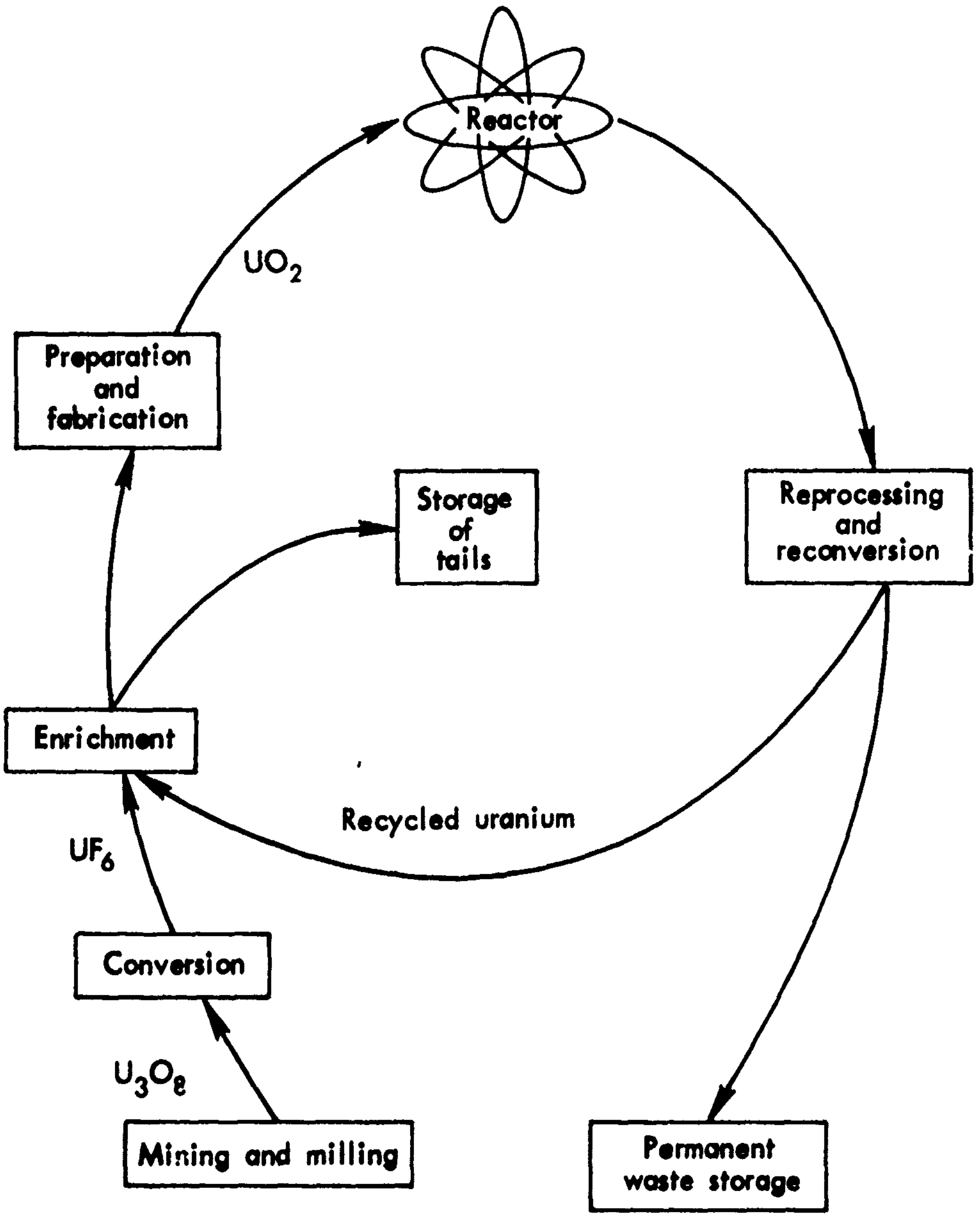

Fig. E-1—Basic nuclear fuel cycle for light-water reactors [11]

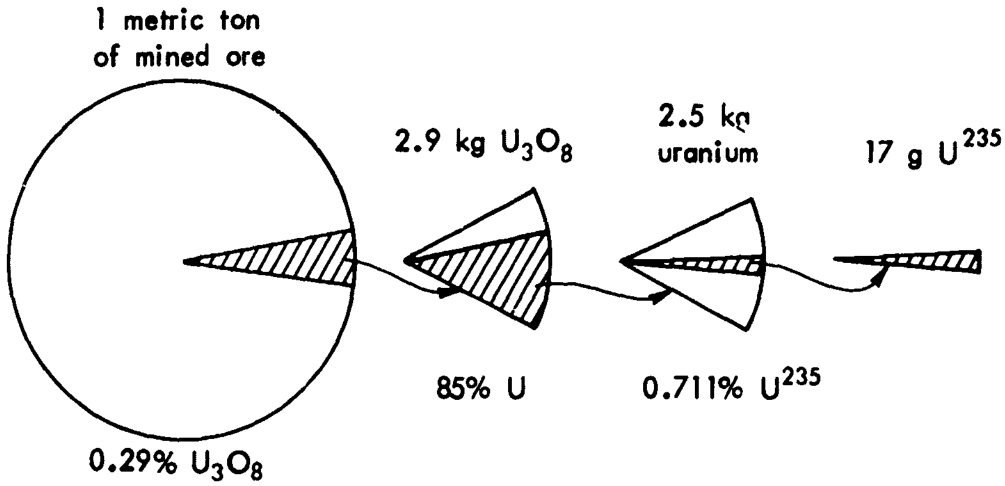

Fig. E-2—One metric ton of ore yields approximately 17 grams of fissile uranium

enriched to between two and three percent U^{235}--depending on the specific reactor design. The core of a typical airborne liquid-metal reactor requires enrichments up to 93 percent.

The energy expended at such a plant is measured in separative work units (SWU) [95]. In addition to the enriched uranium, the plant produces depleted uranium (called tails) with a usual assay of between 0.2 and 0.3 percent U^{235}.

Preparation and Fabrication

During these steps--which at times occur in the same plant [98]--the fuel is readied for use in the reactor. The UF_6 is converted to UO_2, uranium dioxide, a powder, which in turn is pressed into tiny pellets. These pellets are inserted into thin-walled metal tubing (the fuel rods) in a process called cladding. These fuel rods are assembled in groups called fuel elements. (The fuel elements of the ALMR would differ substantially from those of a conventional ground-based reactor.)

As of 1970, there were four such fabrication plants in the United States, with two more scheduled to be in operation by 1976 [93].

Reactor

During the fission process in an LWR, products are formed which absorb neutrons; thus, fewer neutrons are available to maintain the chain reaction. When the process has slowed significantly because of this, the fuel is said to be "poisoned." Periodically, therefore, some of the irradiated fuel is replaced with fresh fuel (on the average, one quarter of the core is replaced each year). The spent fuel is so radioactive that it must be stored at the reactor site for several months before being shipped in lead casks to a reprocessing plant.

The nuclear airplane's liquid-metal-cooled reactor, on the other hand, is designed to provide 10,000 full-power reactor hours between refuelings. At that time, the entire core is replaced. One of the most significant differences in the fuel cycle of the ALMR compared to the LWR's is that the spent core still contains an enormous quantity of unfissioned U^{235}. The energy content of this spent fuel is actually several times larger than that consumed by the reactor in 10,000 hours of operation. It is obviously important to recover the unused fissionable material from the poisoned, irradiated fuel and reprocess it.

Reprocessing and Reconversion

At the reprocessing plant the elements of the spent fuels are chopped into pieces and dissolved in acid to recover the residual uranium and produced plutonium.[a] The uranium is sent to the enrichment plant after being reconverted to UF_6. At present the plutonium is stored, but future plans call for it to be blended with uranium for future use in LWRs (i.e., plutonium recycling [99]).

The permanent wastes (called high-level wastes because of their high radioactivity) are presently stored in underground steel tanks near the reprocessing plants [100]. The most likely permanent disposition of the wastes appears to be underground in solid form in geologically stable areas.

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[a]Plutonium, as noted in the subsequent discussion, can be regarded as a by-product of the fissioning of U^{235}.

The Fission Process

All current reactor concepts have one element in common: They universally use U^{235} at some point in the fission process. The important characteristic of U^{235} is the high probability of its fissioning into fragments whenever it captures a slow-moving free neutron. Fissioning results in the conversion of about 0.1 percent of the original mass of the uranium nucleus into energy. There is an average energy release of about 200 MeV (million electron volts) per fission. Approximately 95 percent of this energy results from primary fission, 5 percent from secondary sources. Fissionable atoms are also removed by parasitic neutron capture, since neutron capture does not always result in fission. The ratio of capture to fission varies with the fissile material and neutron energy [101]. Fission energy appears largely in the form of kinetic motion of the particles (i.e., heat energy).

Along with the fission products, for every neutron required to initiate fissioning, an average of 2.5 neutrons are released. Of course, this is the reason a chain reaction is possible.

As noted earlier, only 0.711 percent of natural uranium is the fissile isotope U^{235}. Fortunately, two other isotopes, which are hundreds of times more abundant than U^{235} [102], can be converted to fissionable material.

Fertile Isotopes. In practice, two man-made isotopes are also capable of sustaining a fission reaction: U^{233} and Pu^{239}. These two isotopes can be produced from thorium and uranium, respectively. The pertinent reactions (with interim steps removed) are:

$$Th^{232} + \text{neutron} \rightarrow U^{233} + \text{electron (27.4 days reaction time)}$$

$$U^{238} + \text{neutron} \rightarrow Pu^{239} + \text{electron (2.37 days reaction time)}$$

In addition to the quantity of fissile Pu^{239} produced, a significant amount of nonfissile plutonium is also produced. Thus, when this plutonium product is discussed, it is customary to indicate the percentage which is fissile. For example, the plutonium product

mixture typical of spent fuel from an LWR initially fueled with slightly enriched uranium is approximately 71 percent fissile. The operating characteristics of the ALMR are such that only a few kilograms of fissile plutonium are produced in the 10,000 hours of operation.

Thus U^{238} and Th^{232} are said to be "fertile" materials because they can decay into the "fissile" materials Pu^{239} and U^{233}, respectively.

The Breeder Reactor. With the above understanding, we can observe that a breeder is simply a reactor designed in such a way that --after a period of time--the quantity of fissile material converted from fertile material is larger than the quantity of fissile material consumed--for example, more fissile plutonium produced than U^{235} consumed. A reactor which produces about as much fuel as it consumes is called a converter; one with a very low conversion rate is called a burner. Most of the reactors in the United States today are burners, as are the airborne liquid-metal-cooled reactors considered in this study.

TOTAL ENERGY ANALYSIS

The objective of our energy analysis of the nuclear fuel cycle is to develop a total energy ratio for nuclear fuel comparable to the energy ratios presented in Section VI for the chemical fuels. Such a ratio provides the means for calculating the nuclear airplanes' total fuel-energy consumption in addition to their direct consumption (i.e., the energy content of the fuel consumed onboard the nuclear airplane).

Figure E-3 illustrates this type of analysis for the supply processes of the chemical fuels--assuming that they are being synthesized from coal. The energy requirements of each step in the supply path have been divided into two components: process energy and resource energy. Process energy is the ancillary energy required at each step; included, for example, is the energy required to mine the coal and to fuel the train, and the electrical energy required by the various

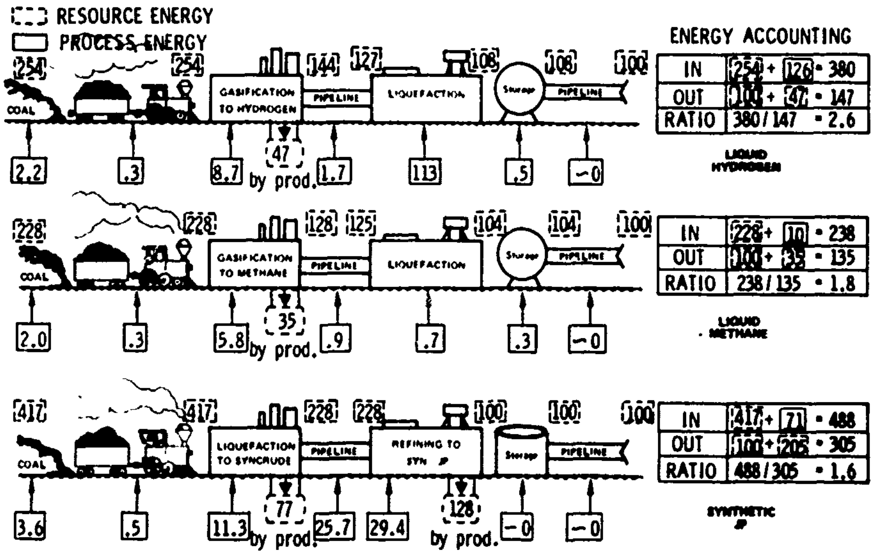

Fig. E-3—Energy flows for chemical fuels synthesized from coal [19]

facilities.[a] The resource energy flows, on the other hand, reflect the thermodynamic losses at each conversion step, and transportation and storage losses (e.g., boil-off of liquid hydrogen). The resource energy flow begins with the coal input required (254 units for the LH_2 case in Fig. E-3); the output consists of the desired fuel end-product (100 units) plus any useful by-products (e.g., the 47 units of low Btu gas output in the hydrogen gasification facility).

As illustrated in Fig. E-3, once the energy flows for a given process are identified, determining the total energy ratio is straightforward. It is simply the sum of the input energy (process and resource) divided by the sum of the output energy (desired end-product plus useful by-products). Figure E-3 gives these total energy ratios for the three synthetic chemical fuels.

[a]Electrical energy here and in the nuclear fuel cycle analysis is represented by the required thermal inputs for the generation of electricity. In other words, one kilowatt-hour of electricity equals 10,480 Btus of heat input--a conversion efficiency of 32.6 percent [19].

Modeling the Nuclear Fuel Cycle

Analogous energy flows in the supply process for nuclear fuels (based on the previously described fuel cycle) are conceptually more complex. The process energy requirements of the nuclear fuel cycle present no difficulty and can be treated in the same fashion as those of the chemical fuels. However, problems arise in the definition of resource energy.

A definition of the total energy ratio for the nuclear fuel cycle that corresponds to the above description of the chemical fuels would be

$$ER = \frac{E_p + E_r}{R_e + B_e} \tag{E-1}$$

where

ER - nuclear fuel cycle total energy ratio

E_p - process energy requirements

E_r - resource energy inputs

R_e - reactor thermal output

B_e - energy content of useful by-products

The process energy and reactor output terms are well defined as is the by-product term, once the meaning of "useful" is agreed upon. (At the least, useful by-products include the energy content of the spent core.)

However, the resource energy term is another matter. A given reactor requires a certain amount of yellow cake (U_3O_8) for its fuel and this quantity of yellow cake can readily be calculated. The question is: What is the energy content of a given amount of yellow cake? The apparently appropriate answer is: The energy content of the U^{235} which can be calculated on the basis of the theoretical maximum thermal energy released from the fissioning of one gram of U^{235}--about 73 million Btu's [101].

However, such an approach would be invalid for most reactors, since some of the U^{238} in the original yellow cake will be converted to Pu^{239}. Some of this plutonium is fissioned within the original reactor, while the remainder will be available for recycling. Thus,

if only the energy content of the U^{235} is counted, total energy ratios less than one are possible because of the ignored U^{238} to Pu^{239} conversion.

To resolve these difficulties, it is necessary to consider the purpose of calculating total energy consumption. For the chemical fuels, total energy consumption calculations provided insights into how the coal resource base might be most efficiently exploited to satisfy aviation fuel requirements. In an absolute sense, however, the total energy consumption metric may be less meaningful. For example, the lowest total energy consumption for the VLA-JP aircraft occurs if the JP is made from crude oil. From the viewpoint of realistic energy policy, however, refining crude oil is less attractive in the longer term than synthetic JP from coal, because the U.S. coal resource base is many times larger than that of crude oil. *Thus, if primary energy resources differ, comparing total energy consumption is only significant when related to the magnitude of the respective resource bases.*

To apply this concept to nuclear fuel, we must assume that the magnitude of the yellow cake resource available is known at least as well as the coal resource. Thus, the total amount of U^{235} available is also known. Assuming that all commercial and operational military reactors are of the burner type, the energy ratio--as defined above--can be applied to the known base. When converter reactors (with or without plutonium recycling) or breeder reactors become available, the size of the nuclear resource base can be increased accordingly. To summarize: the nuclear fuel cycle's total energy ratio (for any burner reactor) will remain constant--but the significance of the energy ratio is dependent on the emergence of the advanced reactor concepts.[a]

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[a]The reason for the increases in the nuclear resource base is that --when calculated in this fashion--the total energy ratio of a successful breeder reactor must be less than one. Converter reactors would have total energy ratios approaching unity. In other words, as breeder reactors are introduced, the fissionable material resource base will actually increase. The eventual upper limit on the magnitude of the resource base is governed by the amount of fertile material available. Breeder reactors do not provide an infinite source of energy, but they do expand the usable resource by several orders of magnitude.

With this background, the energy flows in the fuel cycle for the airborne liquid-metal-cooled reactor will now be described--first the process energy flow and then the resource energy. To aid in the explanation, we have used the 535-MWt (megawatts-thermal) reactor for the VLA-NUC aircraft as a working example.

Process Energy

The major component of the process energy is that required for enrichment. Of an order of magnitude less is the process energy required for the rest of the fuel cycle. The latter has been assigned the value 0.3×10^{12} Btu, which is approximately the total amount of process energy needed for all steps but enrichment in the fuel cycle for a 1000 MWe (megawatts-electric) ground-based light-water reactor [103]. To obtain the energy required for enrichment,[a] the total number of separative work units must be determined.

For the ALMR, the average enrichment of the core is 60 percent; that is, there are 2262 kgU in the core, of which 1357 kg are U^{235}. ERDA (then the Atomic Energy Commission) provides tables that indicate 269,743 kgU (with the naturally occurring enrichment of 0.711 percent) are required as feed for the enrichment plant under these circumstances [95]. The corresponding SWU requirement converts to 4.3×10^{12} Btu [104]. The total process energy (E_p) requirement is therefore approximately 4.6×10^{12} Btu.

Resource Energy

Since the initial makeup of the reactor core is known, it is relatively easy to retrace the steps in the fuel cycle and thus determine the total amount of uranium that must be mined. These calculations are illustrated in Table E-1.

Observe that the losses in the milling and conversion steps are quite small; we have assumed that no enriched fuel is lost in the preparation and fabrication steps or in any transportation operations [103].

[a]Here, we are assuming that enrichment is accomplished with the gaseous diffusion process. Enrichment energy requirements could be reduced by as much as an order of magnitude if the centrifuge enrichment process were available.

Table E-1

RESOURCE ENERGY LOSSES IN THE NUCLEAR FUEL CYCLE
(for a 535-MWt airborne liquid-metal-cooled reactor)

Fuel-Cycle Step	Total Uranium Throughput (kg)	Total Uranium Enrichment (%)	Fissionable Uranium (kg of U^{235})
Mining (ore)	269,743	0.711	1918
Milling (U_3O_8)	268,394	0.711	1908
Conversion ($U_3O_8 \rightarrow UF_6$)	267,052	0.711	1899
Enrichment (UF_6)	2,277	60.00	1366
Conversion ($UF_6 \rightarrow UO_2$)	2,272	60.00	1363
Conversion ($UO_2 \rightarrow UN$)	2,267	60.00	1360
Fabrication (UN)	2,262	60.00	1357
Delivered to reactor	2,262	60.00	1357

NOTE: The fuel elements of the ALMR are fabricated from uranium nitride (UN), those of the ground-based LWR, from uranium dioxide (UO_2).

The total requirement is shown in Table E-1 to be 1918 kg. This can be converted to energy measure by using the aforementioned conversion factor (1 g U^{235} = 73 million Btu). Thus, the resource energy requirement for the reactor core, the E_r, is 140.0 x 10^{12} Btu.

The only useful energy by-product of the ALMR's fuel cycle is the energy content of the spent core. The uranium makeup of the spent core is displayed in Table E-2 along with the associated reprocessing and

Table E-2

REPROCESSING AND RECONVERSION LOSSES
(after 10,000 full-power reactor hours)

Fuel-Cycle Step	Total Uranium Throughput (kg)	Total Uranium Enrichment (%)	Fissionable Uranium (kg of U^{235})
Spent reactor core	1952	55	1069
Reprocessing and reconversion	1938	55	1066
Available for enrichment	1938	55	1066

reconversion losses. (Recall that reprocessing included high-level waste disposal.) The resulting energy content of the by-product, B_e, is 77.8×10^{12} Btu.

Total Energy Ratio

To complete the calculation of the fuel-cycle's energy ratio, we need only the thermal output of the reactor, R_e. During 10,000 hours of full-power operation, a 535-MWt reactor would generate 18.3×10^{12} Btu (1 kwh = 3413 Btu).

From Equation E-1, the total energy can be computed as

$$ER = \frac{(4.6 + 140.0) \times 10^{12}}{(18.3 + 77.8) \times 10^{12}} = 1.50 \qquad \text{(E-2)}$$

The reader is reminded that the above energy ratio is specific to a liquid-metal-cooled reactor intended for aircraft propulsion.[a]

Furthermore, total energy consumption comparisons between the chemical-fueled airplanes and the nuclear airplanes must be made with an awareness of the magnitude of their respective resource bases. This aspect of the energy analysis is further discussed in Section VI.

NUCLEAR FUEL COSTS

In this section, we describe the techniques and procedures used in arriving at the nuclear fuel costs for an ALMR. Since such an airborne reactor has never been built, it is necessary to conceptualize the fuel element fabrication, reprocessing, and reconversion steps in the fuel cycle and to project the cost for each step. This introduces a considerable margin for error, and different analysts may arrive at quite different cost estimates. We have made use of available expertise [105,106] in formulating the various fuel element processes and have

[a]An alternative definition of the energy ratio is: The sum of the process energy plus reactor output divided by the reactor output. Interestingly, this much simpler formulation, which has the advantage of not having to deal with the resource energy flows, yields a comparable value for the energy ratio of 1.39.

relied upon the cost projections made by these experts and other experts within the Energy Research and Development Administration [107, 108, 109, 110].

Unlike the cost of chemical fuels, which are determined prior to their consumption, the cost to DoD of nuclear fuels is determined only after they have been used. This is due to ERDA's policy of charging governmental agencies only for the fissile material consumed and not for the entire uranium inventory originally delivered. Because of this policy we need only estimate the dollar value of the uranium inventory at reactor start-up and again at end-of-life.

Start-Up

Because the depletion of low-cost, high-grade domestic uranium ores is projected to occur by the mid-1980s, the value of the reactor's uranium inventory is based upon the cost factors shown in Table E-3.

Table E-3

PARAMETERS FOR NUCLEAR-FUEL COST ESTIMATES

Cost Parameter	Value	
	Expected	Current
Ore tails assay (% U_3O_8)	0.12	0.29
Ore (\$/kg U_3O_8)	33.00	17.60
Conversion (\$/kgU)	3.42	2.40
Separative work (\$/SWU)	53.35	36.40

If the initial fuel charge follows a typical enrichment sequence before fabrication, it will proceed from ore to reactor fuel as follows:

$$\text{Ore} \rightarrow U_3O_8 \rightarrow UF_6 \rightarrow UO_2 \rightarrow UN$$

Combining the expected ore assay in Table E-3 with the yellow cake requirement shown in Table E-1 indicates that 224,800 metric tons of ore will be required for each ALMR core. Again using Table E-3, each core will contain \$8.9 million in uranium inventory.

The charges for uranium enrichment services are determined by the number of separative work units required to obtain the enrichment desired. The enrichment of a typical ALMR varies from a minimum of 50 percent at the core centerline to a maximum of 93 percent at the periphery, with an overall core average of 60 percent. Although not absolutely exact, cost estimates based upon an overall core average enrichment are sufficiently accurate for our purposes. A total of 148.235 SWU/kg are required for enrichment to 60 percent [107]; hence, an ALMR core would represent an initial investment of $18 million in enrichment services.

End-of-Life

To estimate the end-of-life value, we calculate the core's enrichment ratio after 10,000 full-power hours and determine the value of a clean core of the same enrichment ratio. Since only U^{235} is consumed in quantity, the average enrichment at the end-of-life will be less than at start-up; and its value, as determined from the equivalent ore processed and enrichment services, will likewise be less.

We first estimate the quantity of U^{235} consumed and then determine the average enrichment ratio. To deliver 535-MWt net output requires that the core generate about 543-MWt total, since not all of the thermal energy can be recovered at a high enough temperature to be of propulsive value. An ALMR operating for the full 10,000 hours will consume approximately 288 kg U^{235} (250 kg fissioned and 38 kg lost by parasitic capture). Similarly about 22 kg U^{238} will be removed by neutron absorption (and nearly 13 kg will eventually become fissionable Pu^{239}). In our analysis, in order to maintain a conservative cost estimate, no credit is taken for the Pu^{239}. The end-of-life enrichment is computed to be 55 percent, which represents $14 million in enrichment services and the value of the uranium inventory is $7.3 million.

Thus, the net cost of fissionable material for one ALMR core is estimated to be $5.6 million. To this we must add the costs of reprocessing, waste disposal, and fuel-element fabrication. The cost of reprocessing has been estimated to be $1300 per kgU processed [106]. Using this rate, the reprocessing cost for one core would be $2.5 million. Waste disposal cost has been estimated to be $700 per kgU

[106], for an additional cost of $1.3 million per core. We use LWR experience to estimate the fabrication costs since there are no data available on the fabrication costs of the ALMR-type fuel elements. Light-water reactor experience suggests that fabrication costs are typically about 21 percent of total fuel-cycle cost. Thus, fabrication cost of one core would be approximately $2.5 million.

The resulting total fuel-cycle cost estimates are summarized in Table E-4. Earlier we noted that the total output of the ALMR for

Table E-4

NUCLEAR FUEL-CYCLE COST ESTIMATES
(Per reactor core in 1975 dollars)

Fuel-Cycle Element	Cost
Fissionable material	5,600,000
Reprocessing	2,500,000
Waste Disposal	1,300,000
Fuel-element fabrication	2,500,000
Total	11,900,000

10,000 hours of reactor operation was approximately 18.3×10^{12} Btu. Therefore, the average unit costs (to the Defense Department) of the nuclear fuel is approximately $0.65/MMBtu.

Appendix F

DETAILS OF THE STRATEGIC AIRLIFT MISSION ANALYSIS

This appendix presents those details of the strategic airlift analysis which were omitted, for the sake of brevity, from Section VII. Among the analytical aspects to be discussed are the techniques for determining cycle times (i.e., the total ground and flight time for a complete APOE-to-APOD-and-return cycle), the method of estimating average aircraft payloads, and some important operational considerations. In addition, detailed results are presented for each of the six mission scenarios investigated.

ANALYTICAL ASPECTS

Simulating an airlift deployment requires the specification of numerous parameters. Reduced to simplest terms, the time required by a given fleet of operational aircraft to deploy a specified amount of Army equipment can easily be determined if the cycle-time (i.e., APOE to APOD and return) and the average aircraft payload for that type of equipment are known. Both are discussed below, as is the way closure time for a specified number of UE aircraft is then estimated.

Cycle Time

Estimating the flight time between an APOE-APOD pair obviously requires the specification of the deployment route. Table F-1 lists the equipment weights that must be loaded at each of 24 airfields which served as APOEs in our analysis. Each Army unit deployed is within one day's march of its associated APOE [54].

Table F-1

ARMY UNIT EQUIPMENT WEIGHTS AND ASSOCIATED APOEs
(Tons)

APOE	PREPOSITIONED DIVISIONS		TRICAP DIVISION		82d AIRBORNE DIVISION		9th INFANTRY DIVISION		25th INFANTRY DIVISION		101st AIRMOBILE DIVISION	
	Divisional	ISI	Divisional	ISI	Divisional	ISI	Divisional	ISI	Divisional	ISI	Divisional	ISI
Altus AFB		7,840		1,763		4,865		3,093		755		163
Barksdale AFB		439						805				1,868
Biggs AAF		5,679		3,065		1,224		3,822				
Birmingham Municipal Airport		1,608				786		224				406
Campbell AAF		3,083		4,884		1,680		1,574		3,806	11,057	7,623
Charleston AFB		495						1,043				321
Eglin AFB		2,357		4,366				562				1,043
Forbes AFB	3,007[a]	14,919		1,045				1,043		1,511		
Griffiss AFB										595		
Hickam AFB				533					26,904	5,706		
Homestead AFB		2,452										1,110
Lemoore NAS										2,248		
McChord AFB		1,074		495			26,904	11,797		1,019		
McGuire AFB		1,111		713		1,049		566		1,394		310
Minneapolis International Airport		2,002		7,284				2,920		7,230		623
Norton AFB				374								
Patuxent River NAS		7,813		3,329				3,766		1,768		8,122
Pease AFB		4,775				3,811		3,099				
Peterson Field (AF)	6,689[b]	10,562				3,446		367		503		
Robert Gray AAF	6,357[c]	20,170	44,941	2,431		231		306		367		2,531
Robins AFB		10,751		893		7,625		1,033		1,791		5,473
Seymour Johnson AFB		5,280		437	10,119	13,657		961				1,935
Travis AFB		5,543		599				459				
Whiteman AFB		7,001		3,183						753		234
Totals	16,053	114,954	44,941	35,394	10,119	38,374	26,904	37,350	26,904	29,446	11,057	31,762

SOURCE: U.S. Army Tables of Organizational Equipment, March 1974 [54].

[a]1st Mechanized Infantry Division.

[b]4th Mechanized Infantry Division.

[c]2d Armored Division.

For each mission scenario, flight distances were estimated by subdividing the route from each APOE to the APOD into realistic[a] mission legs. The lengths of the mission legs were tailored to the specific range/radius payload characteristics of each of the alternatives. The flight time (block-to-block) for each leg is given by

$$t_{1_i} = \frac{D_{1_i}}{V_{a_i}} + 25/60 \qquad \text{(F-1)}$$

where

t_{1_i} - flight time on mission leg i (hr)
D_{1_i} - flight distance for mission leg i (n mi)
V_{a_i} - aircraft cruise speed adjusted for average winds on leg i (kn) [3].

Thus, 25 minutes were allotted for taxiing, etc., in each mission leg.

Ground times were estimated as follows:

- 2.5 hours allotted for loading at the APOE
- 2.0 hours for each refueling stop
- 1.0 hours allotted for off-loading at the APOD

The ground time at the APOD for Middle East and Far East range missions was assumed to be 3 hours (to allow for refueling as well as

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[a]Realistic in the following sense: Consider the NATO radius mission as an example. Most sorties included an outbound and inbound refueling stop at Dover AFB or McGuire AFB. However, one, or both, of these stops can be eliminated for some APOEs (e.g., Griffiss AFB or Patuxent River NAS) and in the present analysis they were. A more interesting example is Campbell Army Airfield and the 101st Airmobile Division. Campbell is about 4000 n mi from Frankfurt and, as such, beyond the radius capability of the chemical-fueled VLAs at their design payload. However, as we discuss later in this appendix, the average payloads for an airmobile division are quite small because of the bulkiness of the equipment. With the reduced payload, the VLA-JP can fly a radius mission at Campbell AAF to Frankfurt and was allowed to do so in the simulation. On the other hand, the VLA-LH_2 still requires the outbound refueling stop at Dover AFB. In all instances, of course, the nuclear-powered airplanes fly nonstop legs from the APOE to the APOD.

off-loading). For radius missions and the NATO range mission (in which the first leg of the return flight for the chemical-fueled airplanes was assumed to be from Frankfurt to Mildenhall RAF--only about 500 n mi), the APOD ground time was reduced to one hour.

The total cycle time is the sum of the flight times for each of the mission legs plus the sum of the ground times as determined above. Note that this approach implicitly assumes perfect organization, at both APOE and APOD, on the part of the units being airlifted. Furthermore, problems relating to ground traffic control and dispersal of units from the APOD are not included.

The reader should also be aware that determining the cycle times is strongly dependent on the selection of the mission legs. Our approach is suboptimal in that it does not involve selecting the best mission leg from among all possible mission legs. For example, some refueling stops might be eliminated for some sorties if payload were reduced slightly. Under such circumstances, modestly increased flow rates (i.e., tons per day) might be possible. Nonetheless, we believe our results are representative of how the missions might be planned under actual operational conditions.

Average Payloads

Average aircraft payloads are very much dependent on what type of Army unit is being deployed. For example, the many tanks in an armored division yield substantially heavier average payloads than the bulky but relatively light helicopters of an airmobile division. In the former instance, payloads are generally weight-limited; in the latter, they will tend to be volume-limited. Below we describe the extrapolated approximation we used for estimating average payloads; we then provide a more refined loading-simulation approach for comparison with our approach.

Extrapolated Approximation. Maximum average payloads for the C-5A and C-141A in terms of the type of Army unit being carried are shown in Table F-2. For each case, the payload is expressed as the tons of equipment plus the number of troops that can be accommodated. The average payloads listed in Table F-2 are maximums since they

Table F-2

MAXIMUM AVERAGE PAYLOADS FOR THE C-5A and C-141A/S AIRCRAFT
(Tons of equipment and number of 300-lb troops)

Unit Type	C-5A[a]		C-141A[b]		C-141S[c]	
	Equipment	Troops	Equipment	Troops	Equipment	Troops
Armored	102.7	33	22.0	6	28.6	8
Mechanized infantry	101.5	41	22.0	6	28.6	8
Infantry	80.4	42	18.1	6	23.5	8
Airborne	55.0	64	13.8	7	17.9	9
Airmobile	30.0	71	12.9	7	16.8	9
Average for ISIs[d]	72.7	73	21.9	6	28.5	8

SOURCE: USAF Airlift Planning Factors [3].

[a]For a maximum ACL of 107.7 tons.

[b]For a maximum ACL of 43.3 tons.

[c]Estimated by Rand for a maximum ACL of 38.3 tons.

[d]Estimated by Rand.

are strictly valid only on flight legs on which the maximum allowable cabin loads (ACL) can be carried. For longer flight legs, a reduced ACL will generally reduce the average payload.

We approximated the average payload for the C-141S (i.e., a stretched C-141A) by increasing the payloads listed for the C-141A by the percentage increase in floor area provided by the stretch modification--about 30 percent [2]. The number of troops accommodated was similarly increased. Much of the motivation for the stretch can be inferred from Table F-2. Note the large discrepancy between the C-141A's maximum ACL and its average payloads.

Maximum average payloads for the very large airplane alternatives were approximated using the same technique. In this instance, the average payloads were extrapolated from those of the C-5A. Results for the design-point VLAs are shown in Table F-3. The usable floor

Table F-3

MAXIMUM AVERAGE PAYLOADS FOR THE
DESIGN-POINT VERY LARGE AIRPLANES
(Tons of equipment and number of 300-lb troops)

Unit Type	Equipment	Troops
Armored	216.7	70
Mechanized infantry	214.1	80
Infantry..................	169.6	89
Airborne	116.0	135
Airmobile	63.3	150
Average for ISIs	153.4	150

SOURCE: Derived from Table F-2.

area of the C-5A is about 2607 sq ft, that of the VLA-JP about 5500 sq ft. Therefore, the maximum average payloads for the VLA-JP was assumed to be greater than that of the C-5A by a factor of 2.11. Since all of the design-point VLAs have the same cargo compartment floor areas, their average payloads are identical.[a]

[a]No penalty was included to account for the split cargo compartment of the nuclear airplanes and the way this might reduce load capacity.

Corresponding maximum average payloads for the excursion alternatives are given in Table F-4. Note that we have assumed identical characteristics for the C-5A and C-5B.

Table F-4

MAXIMUM AVERAGE PAYLOADS FOR THE EXCURSION-CASE AIRPLANES
(Tons of equipment and number of 300-lb troops)

Unit Type	C-5B		VLA-LH_2*		VLA-NUC*	
	Equipment	Troops	Equipment	Troops	Equipment	Troops
Armored	102.7	33	260.0	84	122.1	39
Mechanized infantry	101.5	41	257.0	104	120.7	49
Infantry	80.4	42	203.5	106	95.6	50
Airborne	55.0	64	139.2	162	65.4	76
Airmobile	30.0	71	76.0	175	35.7	71
Average of ISIs	72.7	73	184.1	175	86.4	87

SOURCE: Derived from Table F-2.

The astute reader may now be aware of a possible anomaly in our approach. Note that the C-5A's maximum average payload (equipment plus troops) is equal to the maximum ACL in the case of the armored and mechanized divisions. Maximum ACLs for the VLAs (corresponding to the maximum average payloads presented in Tables F-3 and F-4) are listed in Table F-5. One could successfully argue that the maximum average payload for the VLAs should also be equal to the maximum ACL when carrying either armored or mechanized units. That we have chosen not to do so is one of the numerous small biases in our analysis that favor the cryogenic (in this case, only liquid hydrogen) and nuclear-fueled airplanes. That is, for a range mission of 3600 n mi, the latter argument would suggest a greater capability for the VLA-JP and VLA-LCH_4 because of their larger ACLs for this distance, as shown in Table F-5. The rationale for including such biases is discussed in Section IX.

Table F-5

MAXIMUM ALLOWABLE CABIN LOADS (ACL) USED IN DETERMINING MAXIMUM AVERAGE PAYLOADS (Tons)

Aircraft	Maximum[a] ACL	ACL for 3600 n mi Range Mission
VLA-JP	275.0	275.0
VLA-LCH_4	275.0	275.0
VLA-LH_2	275.0	215.0
VLA-NUC	240.0	240.0[b]
C-5B	118.5	85.0
VLA-LH_2*	275.0	267.5
VLA-NUC*	162.5	162.5[b]

SOURCE: Table 6 in Section IV and Appendix C.

[a]As discussed in Appendix C, substantial differences exist in the range capabilities of the alternatives when carrying the maximum ACL.

[b]Capable of essentially unlimited range.

Of course, the average payloads presented in Tables F-2, F-3, and F-4 are strictly valid only when the wind-adjusted critical leg of the mission is such that the maximum allowable cabin load can be carried. However, in the present work we have made the following assumptions. If the ACL for the wind-adjusted critical leg is greater than the maximum average payload (for the maximum ACL), then the average payload (equipment plus troops) is assumed to be equal to the maximum, as given in Tables F-2, F-3, and F-4. If the ACL is less than the maximum average payload, the average equipment payload for a given airplane and division type is given by

$$\bar{P} = \frac{ACL}{1 + \dfrac{0.15\bar{N}_{max}}{\bar{P}_{max}}} \qquad \text{(F-2a)}$$

and

$$\bar{N} = \left(\frac{\bar{P}}{\bar{P}_{max}}\right)\bar{N}_{max} \qquad \text{(F-2b)}$$

where

$\bar{P}$ - average equipment payload (tons)

$\bar{N}$ - number of 300-lb troops accompanying $\bar{P}$

ACL - allowable cabin load (tons)

$\bar{N}_{max}$ - number of 300-lb troops included in maximum average payload

$\bar{P}_{max}$ - maximum average payload, equipment only (tons)

For each aircraft and unit type, $\bar{P}_{max}$ and $\bar{N}_{max}$ are given by Tables F-2, F-3, and F-4. Note that Equations F-2a and b yield average payloads equal to the ACL. The accuracy of this approach will be discussed when we compare this procedure with the more refined approaches for determining average payloads.

First, however, our treatment of the troop movement needs some clarification. As shown in Table F-2, USAF practice is to deploy some troops along with the unit equipment. (At the least, drivers of wheeled and tracked vehicles should accompany the loads.) Troops not deployed with the unit equipment are generally assumed to be deployed by CRAF passerger aircraft.

Table F-6 lists the troop totals for each of the divisions. The careful reader will have observed that, for each unit-type, the number of troops included in the average payload is constant per ton of equipment for all aircraft under consideration.[a] Thus, deploying the given unit's equipment implies that a fixed number of troops will also be deployed. The number of troops so deployed are shown in Table F-6. The remaining troops (also shown) are assumed to be deployed by CRAF. Not surprisingly, the major CRAF passenger requirement is associated with the pre-positioned divisions. Of course, in our effectiveness

[a]The only exceptions are both C-141 models, which have been included for illustrative purposes only.

Table F-6

ASSOCIATED TROOP DEPLOYMENT

Unit	Total Troops [54]	Troops Deployed with Equipment	Troops Deployed by CRAF
1st Mechanized Infantry	10,994	1,215	9,779
2d Armored	16,790	2,053	14,737
4th Mechanized Infantry	16,491	2,702	13,789
ISI	50,890	50,890	—
TRICAP	16,491	14,516	1,975
ISI	14,359	14,359	—
82d Airborne	14,128	11,779	2,349
ISI	16,972	16,972	—
9th Infantry	16,690	14,044	2,646
ISI	15,293	15,293	—
25th Infantry	16,690	14,044	2,646
ISI	11,450	11,450	—
101st Airmobile	17,732	17,732	—
ISI	11,406	11,406	—
Totals	246,376	198,455	47,921

metric as defined in Section VII, only the weight of the troops deployed with the equipment is included.[a]

<u>Comparison with Loading-Simulaton Models</u>. Much more sophisticated approaches exist for determining the average aircraft loading as

[a]Exactly how these troops are accommodated on each of the alternative airplanes has not been explicitly addressed. The C-5A, of course, provides a troop compartment above the cargo compartment. When carrying troops in a C-141A, current practice is to load a special pallet equipped with troop seats. The VLA-JP could include an upper troop compartment similar to the C-5's (see Appendix A). The matter is more complex, however, for the other VLAs. The cryogenic-fueled airplanes utilize the area above the cargo compartment for fuel tanks; careful design might allow enough space forward of the tanks for a troop compartment. If not, then palletized seats would have to be employed (with a corresponding potential reduction in averate equipment payloads). The nuclear airplanes, as configured in this study, could provide a crew compartment just aft of the flight deck; such a compartment would be similar to the upper lounge of a 747 (see Appendix A).

a function of allowable cabin load (i.e., the average payload function). These consist of a computer simulation of the loading of each piece of unit equipment aboard the airplane. By repeating the simulation for a series of allowable cabin loads, an average payload function can be generated.

Illustrative average payload functions for the design-point VLAs are presented in Fig. F-1. Two division types--armored and airmobile--

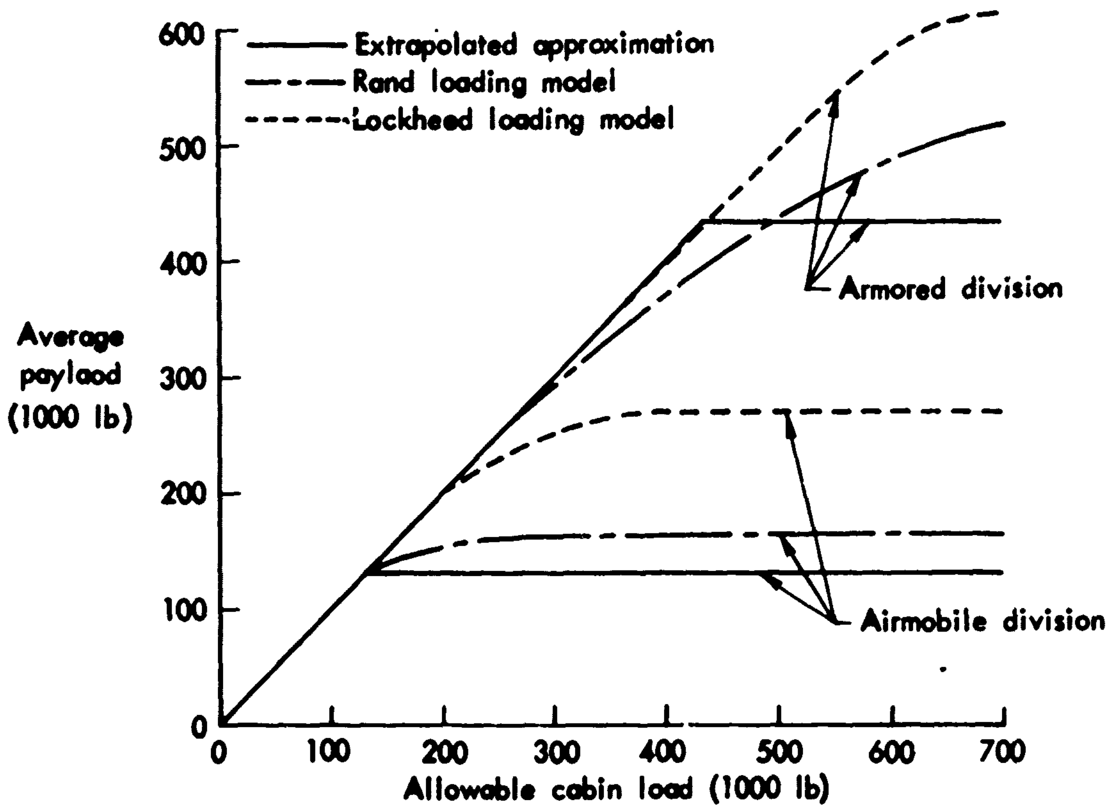

Fig. F-1—Illustrative average loading functions for the design-point VLA cargo compartments

have been examined; they represent the extremes of average equipment densities. One set of functions is based on a loading model developed at Rand several years ago [62]. The other set has been generated by Lockheed-Georgia[a] using their loading model. Also represented are the approximations we used in our analysis and have just described.

A careful examination of Fig. F-1 reveals a significant difference in the functions as determined by the two loading simulation models. This is probably inevitable, given the complexity of the simulation process. Note that our extrapolated approximations usually provide average payloads that are less than or equal to those determined by the loading models. For this reason, our results on the effectiveness of the VLAs in the strategic airlift role can probably be regarded as conservative.

Had computer-generated average loading functions as shown in Fig. F-1 been utilized, the effect would have been most beneficial to the VLA-JP and VLA-LCH_4 alternatives. With the Rand model, for example, the VLA-JP average payload when carrying an armored division on a 3600 n mi range mission is about 463,000 lb. On the same mission, the average payload for the VLA-LH_2 is only 388,000 lb and for the VLA-NUC about 420,000 lb (see Table F-5). Thus, the extrapolated approximation provides average payloads that are much less biased in favor of the VLA-JP. This is consistent with the general policy we have followed throughout this analysis.

In summary, we feel that somewhat more realistic effectiveness results could have been obtained by employing a loading simulation model. We seriously doubt, however, that such an approach would have been worth the substantial cost of running the simulation models--at least, for the purposes of the present analysis.

Operational Readiness Rate

An additional factor that must be included in the deployment analysis is the operational readiness of the available UE aircraft. The official definition of operation readiness (OR) [43] is

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[a]The authors are grateful to Messrs. R. L. Rodgers and D. R. Scarbrough of the Lockheed-Georgia Co. for having provided these examples.

$$OR = \frac{t_{UE} - (t_{ms} + t_{mu} + t_s)}{t_{UE}} \tag{F-3}$$

where

t_{UE} - base hours possessed (as a UE aircraft)

t_{ms} - base hours in scheduled maintenance

t_{mu} - base hours in unscheduled maintenance

t_s - base hours awaiting spares, etc.

In our deployment analyses, we have assumed that if an airplane is operationally ready, it is either flying or being loaded, off-loaded, or refueled.

Conceptually, the time required by a given fleet of aircraft to deploy a given unit from a single APOE to an APOD is given by

$$T = \left[\frac{t_c}{24(OR)}\right]\left[\frac{W_D}{\overline{P}(N_{UE})}\right] \tag{F-4}$$

where

T - deployment time (days)

t_c - cycle time (hours)

W_D - total unit weight (tons)

N_{UE} - number of UE aircraft

$\overline{P}$ - average equipment payload (tons), see Eq. F-2a.

That is, including the OR rate has the effect of converting the operational cycle time into the time actually required (i.e., including maintenance, etc.) for the cycle.

As mentioned previously, the deployment model exercised in the present analysis is a modification of one developed recently by Higgins [60]. It is designed to perform the tedious bookkeeping associated with the deployment of approximately 100 unit type/APOE pairs (Table F-1). Equation F-4 is the heart of this model.

One additional feature of the model is its ability to limit the number of aircraft being loaded at any given time. In our work, we assumed that no more than six aircraft could simultaneously be in the loading process at a single APOE.

The original deployment model is fully documented in Ref. 61. Most of our changes facilitate using the model for different scenarios (i.e., automating much of the input requirements). In addition, either the desired UTE rate or OR rate can be specified a priori (with the other being determined by the model). Alternatively, the desired closure time can be input; in this case the necessary OR rate is determined.

Determining the Tanker/Airlifter Mix

To complete the description of our approach to the strategic airlift analysis, we explain below how the split was made between tankers and airlifters (when tankers are necessitated by mission requirements). If the number of UE airlifters (N_A) are known, then the tanker requirement can be estimated (for buddy mission refuelings) by

$$N_T = \frac{1}{24(OR_T)}\left(\frac{2D_t}{V_c} + 2.42\right)S \qquad \text{(F-5)}$$

where

N_T - number of tankers required to support N_A airlifters
OR_T - tanker operational readiness rate
D_t - distance from base to fuel transfer point (n mi)
V_c - tanker cruise speed (kn)
S - sorties per day being flown by the N_A airlifters

Under rendezvous mission rules, the number of tankers is

$$N_T = \frac{1}{24(OR_T)}\left(\frac{2D_t + 200}{V_c} + 2.42\right)S \qquad \text{(F-6)}$$

The second term in brackets in both equations includes taxiing and climbout times; the parameter "200" in Equation F-6 is a loiter-time allowance at the rendezvous point.

If some total number of UE (N_{UE}) must be split between tankers and airlifters, then Equations F-5 and/or F-6 must be used to calculate the tanker requirement (N_T), assuming first, that all N_{UE} aircraft are airlifters. Then, the split is determined by

$$N_A = \left[\frac{N_{UE}}{1 + \left(\frac{N_T}{N_{UE}}\right)}\right] \qquad \text{(F-7)}$$

and

$$N_T = N_{UE} - N_A \qquad \text{(F-8)}$$

Equations F-5 through F-8 have been employed in determining the tanker requirements for each of the airlift mission scenarios. In all instances, the tanker OR rate was assumed to be equal to that of the airlifters.

Implicit in Equations F-6 through F-8 is a "perfect scheduling" assumption. That is, Equations F-5 and F-6 presume that when the tanker is operationally ready, it is either flying, taxiing, or being refueled. Thus, no time is allotted for the tanker to wait for the incoming airlifter. Stated another way, we have assumed that when an airlifter is ready to take off with a buddy tanker or is preparing to rendezvous with one, a tanker is available.

Since all of the chemical-fueled alternatives require tanker support in some scenarios, the importance of this assumption should be minimized relatively. Obviously, however, if such perfect scheduling (or near perfect) is a practical impossibility, some advantage will accrue to the nuclear airplanes in those missions where tankers are required by the other alternatives. We believe this advantage would be insufficient to enhance substantially the relative attractiveness of the nuclear airplanes, as depicted in Table 21 (Section VII).

COMPLETE MISSION ANALYSIS RESULTS

For completeness, detailed results for each of the six deployment mission scenarios are presented below.

NATO Scenarios

Table F-7a displays detailed results for the NATO-range-mission scenario; NATO-radius-mission results, previously given in Table 20, are repeated as Table F-7b. (For a description of the meaning of the entries in Table 20, see Section VII.)

Several interesting observations emerge from a comparison of the NATO range and radius-mission results. Note first that none of the alternatives requires tanker support for the range mission; the C-5B and the enhanced MAC fleet do require tankers for the radius mission. Not surprisingly, the C-5B suffers a substantial loss of capability (in terms of closure days) when 68 of the available 225 UE must serve in the tanker role (Table F-7b).

When the closure days of the VLA alternatives for the range and radius missions are compared, the result may at first seem counter-intuitive. As one would expect, the VLA-JP can deploy the Army somewhat more rapidly when flying range missions. But the closure times turn out to be the same for the VLA-LCH_4, and the VLA-LH_2 actually requires longer to close under range mission conditions. There are two reasons for this phenomenon. When traveling between APOEs in eastern CONUS and the APOD, the VLA-JP can often fly a direct range mission from the APOE. We have assumed, however, that liquid methane and/or liquid hydrogen is available only at certain bases (see Fig. 22); thus, both the VLA-LCH_4 and VLA-LH_2 must occasionally make extra refueling stops. (Note the somewhat lower UTE rates, i.e., flying hours per day, that result.) Because of the range-payload characteristics of the VLA-LH_2, its performance is particularly affected in this regard. The VLA-LH_2 can carry an armored division's maximum average payload (454,400 lb) only about 3000 n mi on a range mission. Corresponding performance for the VLA-JP is approximately 5200 n mi and about the same for the VLA-LCH_4 (see Appendix C).

A comparison of the closure times for the nuclear airplanes indicates equally unexpected results.[a] Only two differences exist

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[a]Remember that all closure times shown for the nuclear airplanes presume that these aircraft are permitted to overfly the United States with the reactor in operation.

Table F-7a

DETAILS OF THE STRATEGIC AIRLIFT ANALYSIS FOR THE NATO RANGE MISSION

Scenario Parameter	C-5M/ C-141S (KC-135)	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational								
UE transports	70/234	225	112	112	112	112	96	194
UE tankers	0	0	0	0	0	0	0	0
OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	10.0	9.7	10.3	10.0	10.0	11.1	10.0	11.1
Costs (billions 1975 $)								
Acquisition	-	8.5	15.5	16.5	13.6	32.1	15.1	34.8
20-year O&S	-	18.0	16.4	18.8	21.4	24.6	22.5	30.6
Energy (Quads)								
Aircraft manufacture	-	0.16	0.29	0.31	0.25	0.65	0.28	0.74
20 years' fuel	-	2.42	1.84	2.20	2.63	5.25	2.82	6.63
Capability								
Closure days	83	59	52	55	57	45	56	46
Cargo/troops deployed (kilotons)	423/30	423/30	423/30	423/30	423/30	423/30	423/30	423/30
Net fuel balance (kilotons)	-577.5	-407.2	-206.5	-189.4	-202.0	24.5	-230.3	-125.7
Sorties flown	11,198	5,768	2,734	2,734	2,743	2,734	2,278	4,853
Cost-Effectiveness ($ bil/kiloton/day)	-	3.45	3.66	4.29	4.40	5.63	4.65	6.64
Energy-Effectiveness) (Quads/kiloton/day)	-	0.336	0.244	0.305	0.362	0.586	0.383	0.743

Table F-7b

DETAILS OF THE STRATEGIC AIRLIFT ANALYSIS FOR THE NATO RADIUS MISSION

Scenario Parameter	C [illegible]4/ [illegible]41S ([illegible]5)	C-5B	VLA-JP	VLA-LCH$_4$	VLA-LH$_2$	VLA-NUC	VLA-LH$_2$*	VLA-NUC*
Operational								
UE transports	70/234	[illegible]57	112	112	112	112	96	194
UE tankers	(128)	68	0	0	0	0	0	0
OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	10.4	10.4	10.5	10.5	10.5	11.8	10.5	11.8
Costs (billions 1975 $)								
Acquisition	-	8.5	15.5	16.5	13.6	32.1	15.1	34.8
20-year O&S	-	18.0	16.4	18.8	21.4	24.6	22.5	30.6
Energy (Quads)								
Aircraft manufacture	-	0.16	0.29	0.31	0.25	0.65	0.28	0.74
20 years' fuel	-	2.42	1.84	2.20	2.63	5.25	2.82	6.63
Capability								
Closure days	80	79	55	55	55	44	53	44
Cargo/troops deployed (kilotons)	423/30	423/30	423/30	423/30	423/30	423/30	423/30	423/30
Net fuel balance (kilotons)	43.4	40.1	48.1	51.0	34.0	42.5	53.4	110.8
Sorties flown	25,06[illegible]	11,537	2,832	2,832	2,832	2,832	2,334	4,904
Cost-Effectiveness ($ bil/kiloton/day)	-	4.24	3.50	3.85	3.95	5.04	3.94	5.10
Energy-Effectiveness) (Quads/kiloton/day)	-	0.413	0.234	0.274	0.325	0.524	0.324	0.576

between the range and radius profiles of the nuclear airplanes: (1) the maximum ACL is increased for the range mission (as described in Section IV) and (2) the ground time at the APOD is increased from one to three hours, as noted earlier in this appendix. The results shown in Tables F-7a and b indicate that the decrease in UTE rate caused by increased turnaround time offsets any advantage provided by the slightly larger ACLs for the range mission. These same phenomena also affect the relative closure times of the chemical-fueled VLAs on the range and radius missions.[a] Note that in the range mission scenarios the VLA-NUC even shows a positive fuel balance (i.e., more fuel is delivered than is required for the return leg). Remember, of course, that the nuclear airplanes skip the refueling stop at Mildenhall RAF.

Also note in Table F-7a that despite the C-5B's being the most attractive alternative in terms of cost-effectiveness, it does require almost twice as much fuel for the return leg as do the chemical-fueled VLAs. Finally, the total number of sorties flown by the VLAs is substantially smaller in all cases; this may have some positive effect on air-traffic control problems.

Middle East Missions

Similar detailed results for the Middle East scenarios are presented in Tables F-8a and b. For these cases, substantial differences exist between the range and radius mission closure times--at least, for the chemical-fueled airplanes--because of the number of available UE that must serve as tankers.

Observe that the only difference for the enhanced MAC fleet is the number of KC-135As employed. Fc. the radius mission, both the enhanced MAC fleet and C-5B cases require that a significant amount of fuel be removed from the APOD. As noted earlier, such an extreme radius mission is beyond the reasonable capability of the contemporary airplanes.

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[a]In actual operation, if such phenomena were observed the hydrogen and nuclear-fueled airplanes would obviously always fly radius missions to NATO--regardless of the fuel supply situation at the APOD.

Table F-8a

DETAILS OF THE STRATEGIC AIRLIFT ANALYSIS FOR THE MIDDLE EAST RANGE MISSION

Scenario Parameter	C-5M/ C-141S (KC-135)	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational								
UE transports	70/234	175	112	112	112	112	96	194
UE tankers	(175)	50	0	0	0	0	0	0
OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	10.9	10.9	11.0	11.0	10.9	11.9	11.0	11.9
Costs (billions 1975 $)								
Acquisition	-	8.5	15.5	16.5	13.6	32.1	15.1	34.8
20-year O&S	-	18.0	16.4	18.8	21.4	24.6	22.5	30.6
Energy (Quads)								
Aircraft manufacture	-	0.16	0.29	0.31	0.25	0.65	0.28	0.74
20 years' fuel	-	2.42	1.84	2.20	2.63	5.25	2.82	6.63
Capability								
Closure days	84	75	56	57	58	49	56	50
Cargo/troops deployed (kilotons)	292/21	292/21	292/21	292/21	292/21	292/21	292/21	292/21
Net fuel balance (kilotons)	-678.9	-635.2	-458.5	-520.5	-427.8	20.8	-440.2	76.3
Sorties flown	23,288	8,220	1,948	1,945	1,973	1,910	1,630	3,390
Cost-Effectiveness ($ bil/kiloton/day)	-	6.46	5.70	6.42	6.48	8.86	6.72	10.43
Energy-Effectiveness) (Quads/kiloton/day)	-	0.617	0.380	0.456	0.533	0.922	0.554	1.176

Table F-8b

DETAILS OF THE STRATEGIC AIRLIFT ANALYSIS FOR THE MIDDLE EAST RADIUS MISSION

Scenario Parameter	C-5M/ C-141S (KC-135)	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational								
UE transports	70/234	138	79	59	72	112	59	194
UE tankers	(366)	87	33	53	40	0	37	0
OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	10.9	10.9	11.4	11.4	11.4	12.6	11.4	12.6
Costs (billions 1975 $)								
Acquisition	-	8.5	15.5	16.5	13.6	32.1	15.1	34.8
20-year O&S	-	18.0	16.4	18.8	21.4	24.6	22.5	30.6
Energy (Quads)								
Aircraft manufacture	-	0.16	0.29	0.31	0.25	0.65	0.28	0.74
20 years' fuel	-	2.42	1.84	2.20	2.63	5.25	2 82	6.63
Capability								
Closure days	84	95	98	100	84	49	85	48
Cargo/troops deployed (kilotons)	292/21	292/21	292/21	292/21	292/21	292/21	292/21	292/21
Net fuel balance (kilotons)	-347.0	-274.1	26.1	116.3	52.9	34.1	83.9	80.6
Sorties flown	38,648	12,330	4,976	5,730	3,908	1,986	3,218	3,427
Cost-Effectiveness ($ bil/kiloton/day)	-	63.90	9.21	8.21	8.02	7.99	8.04	7.97
Energy-Effectiveness) (Quads/kiloton/day)	-	6.221	0.615	0.584	0.660	0.832	0.663	0.898

The Middle East radius mission is the situation in which the nuclear airplanes appear most attractive. Their closure times are about half those of the chemical-fueled VLAs. (Despite this enormous advantage in effectiveness, the VLA-NUC is only 13 percent more cost-effective than the VLA-JP.) Observe also the very high UTE rates the nuclear airplanes are able to maintain in the radius mission scenario.

Far East Missions

Tables F-9a and b provide the results for the Far East airlift scenarios. For the range mission, all airplanes are permitted to make refueling stops at Andersen AFB as well as Hickam AFB, if doing so reduces closure time. In the radius mission scenario, the stop at Hickam can be eliminated except for the C-5B. All chemical-fueled airplanes then fly radius missions from Andersen to the APOD; the nuclear airplanes, of course, fly radius missions from the APOE to the APOD.

As in the NATO scenarios, all VLAs can deploy the Army units either in the same time or somewhat faster when flying radius missions, and the explanations for this are the same.[a]

Table F-9a also shows that, despite its favorable cost-effectiveness, the C-5B requires a significant amount of fuel at the APOD for the return leg. All of the VLAs have sufficient excess capacity to yield a positive fuel balance at the APOD.

Interestingly, the nuclear airplanes do not appear particularly attractive in these scenarios, even though extreme flight distances are required. This is a demonstration of the importance of en route refueling stops. Although the flight distances here are considerably greater than in Middle East missions, the chemical-fueled alternatives can stop en route for fuel with only modest penalties in closure time, and the nuclear airplanes prove to be relatively less cost-effective.

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[a]We should note that the closure times for the VLAs on the range missions (particularly the VLA-JP and VLA-LCH_4) would have been improved if we had incorporated in the analysis the more optimistic view of their maximum average payloads that we discussed earlier in this appendix.

Table F-9a

DETAILS OF THE STRATEGIC AIRLIFT ANALYSIS FOR THE FAR EAST RANGE MISSION

Scenario Parameter	C-5M/ C-141S (KC-135)	C-5B	VLA-JP	VLA-LCH$_4$	VLA-LH$_2$	VLA-NUC	VLA-LH$_2$*	VLA-NUC*
Operational								
UE transports	70/234	225	112	112	112	112	96	194
UE tankers	0	0	0	0	0	0	0	0
OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	10.7	10.7	11.4	11.0	11.0	12.2	11.0	12.2
Costs (billions 1975 $)								
Acquisition	-	8.5	15.5	16.5	13.6	32.1	15.1	34.8
20 year O&S	-	18.0	16.4	18.8	21.4	24.6	22.5	30.6
Energy (Quads)								
Aircraft manufacture	-	0.16	0.29	0.31	0.25	0.65	0.28	0.74
20 years' fuel	-	2.42	1.84	2.20	2.63	5.25	2.82	6.63
Capability								
Closure days	106	75	66	69	69	59	67	60
Cargo/troops deployed (kilotons)	292/21	292/21	292/21	292/21	292/21	292/21	292/21	292/21
Net fuel balance (kilotons)	-215.0	-183.9	133.4	130.6	56.1	20.7	69.9	76.4
Sorties flown	8,054	4,113	1,910	1,910	1,910	1,910	1,591	3,390
Cost-Effectiveness ($ bil/kiloton/day)	-	6.34	6.72	7.77	7.70	10.67	8.04	12.52
Energy-Effectiveness) (Quads/kiloton/day)	-	0.579	0.448	0.552	0.634	1.110	0.663	1.411

Table F-9b

DETAILS OF THE STRATEGIC AIRLIFT ANALYSIS FOR THE FAR EAST RADIUS MISSION

Scenario Parameter	C-5M/ C-141S (KC-135)	C-5B	VLA-JP	VLA-LCH$_4$	VLA-LH$_2$	VLA-NUC	VLA-LH$_2$*	VLA-NUC*
Operational								
UE transports	70/234	183	112	112	112	112	96	194
UE tankers	(57)	42	0	0	0	0	0	0
OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	11.1	11.1	11.5	11.2	11.2	12.8	11.2	12.8
Costs (billions 1975 $)								
Acquisition	-	8.5	15.5	16.5	13.6	32.1	15.1	34.8
20 year O&S	-	18.0	16.4	18.8	21.4	24.6	22.5	30.6
Energy (Quads)								
Aircraft manufacture	-	0.16	0.29	0.31	0.25	0.65	0.28	0.74
20 years' fuel	-	2.42	1.84	2.20	2.63	5.25	2.82	6.63
Capability								
Closure days	102	89	65	68	69	58	67	58
Cargo/troops deployed (kilotons)	292/21	292/21	292/21	292/21	292/21	292/21	292/21	292/21
Net fuel balance (kilotons)	142.2	132.1	134.6	131.7	64.0	33.7	76.4	80.6
Sorties flown	16,112	8,226	1,915	1,915	1,951	1,984	1,618	3,427
Cost-Effectiveness ($ bil/kiloton/day)	-	5.29	4.63	5.39	6.40	9.47	6.46	9.63
Energy-Effectiveness) (Quads/kiloton/day)	-	0.515	0.309	0.383	0.526	0.986	0.533	1.085

Appendix G
DETAILS OF THE STATION-KEEPING MISSION ANALYSIS

Additional aspects of our analytical approach to the station-keeping missions are presented in this appendix. Estimates of life-cycle costs and life-cycle energy consumption for the station-keeping fleets can be generated with the previously described methodology. The main thrust of this appendix is to give a more detailed explanation of how the mission effectiveness parameters were developed.

For completeness, detailed results for each of the station radii highlighted in Section VIII are included--for both the 12-hr and 324-hr minimum time-on-station cases.

MISSION EFFECTIVENESS

Because of their obviously divergent performance attributes, mission effectiveness is determined in wholly different ways for the chemical-fueled airplanes and the nuclear airplanes; they will, in consequence, be discussed separately.

Chemical-Fueled Airplanes

The measure of mission effectiveness ascribed to the station-keeping role is the maximum payload tonnage that c be continuously maintained on-station by a specified fleet of airplanes. Depending on the desired station radius and station-keeping duration for each individual carrier aircraft (i.e., the time-on-station), some fraction of the fleet will serve as carriers and the remainder provide tanker support for these carriers. Therefore, the total tonnage maintained on-station is equal to the specified mission payload and the average number of UEs on-station at any given moment.

Approach. Our approach is to specify the mission payload, station radius, and minimum time-on-station. The maximum number of UEs that can be maintained on this station, for a given fleet size and operational readiness, is then determined by considering six operational

flight profiles--with the maximum defined as the best of these six ways of performing the mission.[a] The six operational profiles are:

- o Operational Profile 1
  - Each UE carrier operates without any tanker support (i.e., all available UE serve as carriers)
- o Operational Profile 2
  - The UE carrier flies to the station-keeping point without tanker support
  - While on-station, the carrier is periodically refueled by a tanker under rendezvous rules
  - The tanker's fuel off-load corresponds to that for a radius mission of length equal to the specified station radius
- o Operational Profile 3
  - The UE carrier flies to the station-keeping point without tanker support and is periodically refueled by a tanker under rendezvous rules
  - The carrier's tanker receives an outbound in-flight refueling (buddy rules) from another tanker
- o Operational Profile 4
  - The UE carrier receives a buddy in-flight refueling on its outbound flight to the station-keeping point
  - While on-station, the carrier is periodically refueled by a tanker which has received an outbound refueling from another tanker
- o Operational Profile 5
  - The UE carrier receives an outbound refueling en route to the station-keeping point and is periodically refueled by a tanker

[a]Of course, all six profiles are seldom applicable to a particular station radius/time-on-station combination. Those not applicable to a given situation are discarded out of hand.

  - The carrier's tanker receives an outbound in-flight refueling and an inbound refueling (rendezvous rules) from other tankers
- Operational Profile 6
  - The UE carrier receives an outbound refueling en route to the station-keeping point; while on-station, the carrier is refueled by a tanker which receives outbound and inbound refuelings from other tankers
  - The UE carrier receives an in-flight refueling (rendezvous rules) on its flight from the station-keeping point to the home base

Still more complex operational profiles could be considered. However, we believe that their very complexity might preclude their use under real-world conditions.

In analyzing each of the above operational profiles, two conventions were uniformly applied:

1. All tanker and carrier operations are assumed to originate and terminate at the same base.
2. While on-station, the carrier's refueling is timed in such a way that the fuel onboard the carrier is never less than the amount required to complete the inbound leg. (For Profiles 2 through 5, this is enough fuel to return to base; for Profile 6, it is sufficient to meet the rendezvous tanker inbound.)[a]

The second convention can lead to the following situation: For certain station radii, the fuel required for the inbound leg is such that the

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[a]Thus, the carrier receives no additional in-flight refuelings after the minimum time-on-station is achieved; the carrier then remains on-station until just enough fuel remains to complete the inbound leg. The actual time-on-station is therefore determined.

off-load capability of the tanker is substantially greater than the available fuel capacity of the carrier. When this occurs, we assume that the tanker can service as many as three carriers, which are all presumed to be operating in the same vicinity. To do otherwise would penalize, perhaps artificially, the tanker's utility, since this situation only arises because of the second convention.

The above profiles can be analyzed by extending the methodology presented in Appendix C. Table G-1 presents the only additional airplane characteristic required--namely the average fuel consumption

Table G-1

AVERAGE FUEL CONSUMPTION DURING LOITER

	MMBtu/hr	lb/hr
VLA-JP	738	39,700
VLA-LCH_4	795	37,000
VLA-LH_2	649	12,600
C-5B	474	25,500
VLA-LH_2*	796	15,400

during the loiter phase of the profile. These consumption rates assume the VLAs are carrying their respective design payloads; the C-5B payload is assumed to be 200,000 lb.

Other operational aspects of the station-keeping analysis are comparable to the strategic airlift mission analysis. These include operational readiness (0.58 for both carriers and tankers), ground refueling time (two hours), and ground operational time (taxiing, etc. --25 minutes per sortie.) The technique for splitting the fleet between carriers and tankers (for each station radii/time-on-station pair) is analogous to that outlined in Appendix F.

Illustrative Example. Figure G-1 illustrates the application of the above approach in determing the on-station performance of the VLA-JP. Shown is the payload maintained on-station in terms of station radius for several combinations of specified minimum times-on-station and individual carrier's mission payload. Several important insights are provided by this illustration.

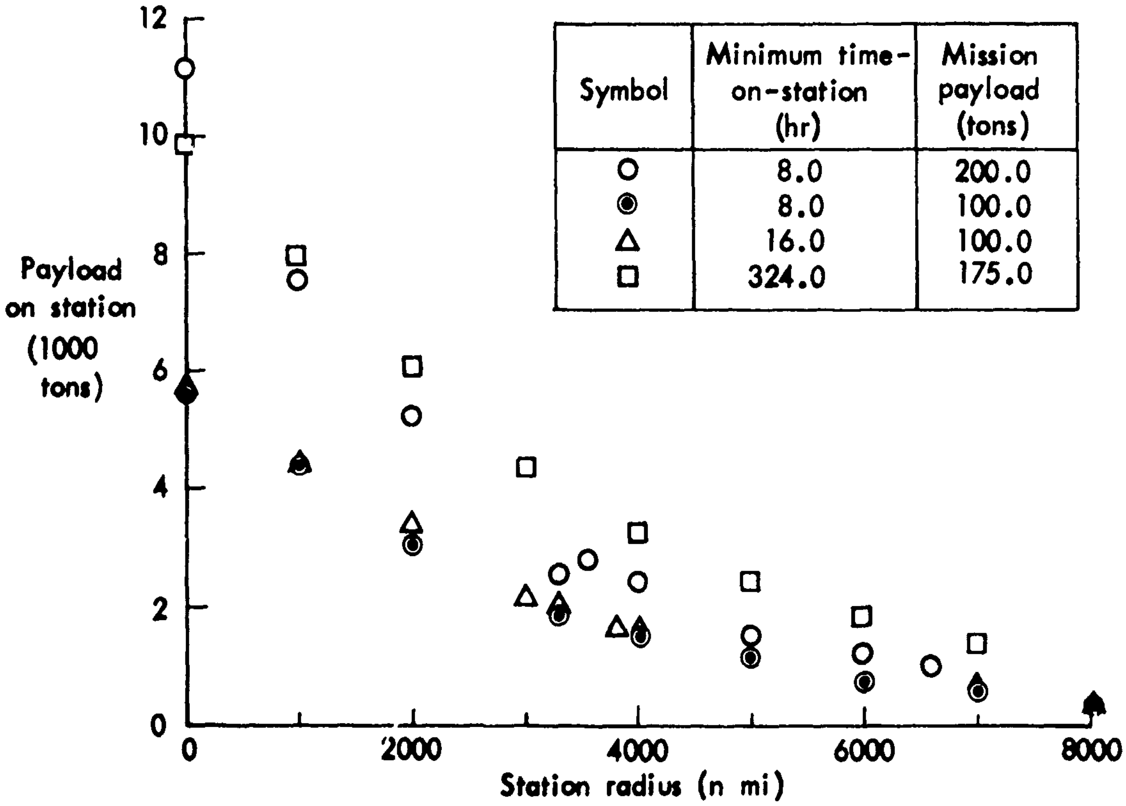

Fig. G-1—Illustrative on-station performance of the VLA-JP

First, compare the effect of different mission payloads when the minimum time-on-station is fixed. At any station radius, the larger mission payload case (i.e., 200 tons) provides a significantly greater effectiveness. In our analysis of the station-keeping missions, we have assumed that the mission payload for each of the VLAs is equal to the design payload; for the C-5B, 200,000 lb was specified as the mission payload. Thus, the average floor loading for each of the VLAs is constant. This seems appropriate since the makeup of the payload is unspecified and would most likely be very mission dependent. The floor loading of the C-5B with a 200,000 lb payload is somewhat greater; the effectiveness measure for this alternative might therefore, in a relative sense, be slightly optimistic.

The second important observation about Fig. G-1 concerns the effect of varying the minimum time-on-station while holding the mission payload constant. When the 8-hr and 16-hr cases are compared, a slightly greater capability is always observed for the longer station-keeping duration. As mentioned previously, this is because the carriers waste less available operational time flying to and from the station-keeping point.

Also displayed in Fig. G-1 are the results for the 324-hr minimum time-on-station carrying the design payload. Note that a relatively smooth curve can be drawn through the symbols for this case. The curves for other times-on-station are much less regular. This is a consequence of our having fixed the mission payload and station radius and then examining only six distinct operational flight profiles. Under these circumstances, an increased capability can sometimes be provided by slightly lengthening the station radius; the improvement is a consequence of having achieved a more favorable match between operational profile and the specified mission payload. Relaxation of the aforementioned two conventions would subdue such irregularities. Our determination of the capability of each alternative (e.g., as in Tables G-2, etc.) at each of the five selected station radii is consequently derived from a smoothly faired curve which encompasses the upper-bound envelope of the set of distinct effectiveness estimates

for the specified minimum time-on-station. See Fig. 24 in Section VIII, for example.

Nuclear Airplanes

The determination of station-keeping mission effectiveness for the nuclear airplanes is considerably more straightforward since only Operational Profile 1 need be considered. Furthermore, for a specified time-on-station and station radius, the average number of UE on-station is invariant for any mission payload between the design and maximum values (the mission payload being determined by the emergency recovery range desired). Indeed, the number of UE aircraft on-station is given simply by

$$N_s = OR\left(\frac{T_s}{2(R_s/V_c) + 2.42 + T_s}\right)N_A \qquad \text{(G-1)}$$

where

N_s - Average number of UE on-station
OR - Operational readiness rate (0.58)
T_s - Time-on-station (hours)
R_s - Station radius (n mi)
V_c - Cruise speed (knots)
N_A - Number of UE available

Note that because the nuclear airplanes are not affected by the aforementioned in-flight refueling convention, the actual time-on-station can be specified.

The total tonnage maintained on-station is the product of the average number of UE on-station and the mission payloads for the individual aircraft. Throughout this analysis, the mission payloads for both nuclear airplanes have been assumed to be their design payloads. Thus, the average floor loadings in the station-keeping missions for the chemical-fueled and nuclear-fueled VLAs is approximately constant. Under these circumstances, the VLA-NUC and VLA-NUC* aircraft could carry sufficient JP on board to provide a 1250 n mi emergency recovery range (see Appendix A).

Of course, if both nuclear airplanes carried their maximum payloads, they would retain an emergency recovery range of only about 850 n mi. If this recovery range were deemed acceptable, mission effectiveness would be correspondingly enhanced. However, as we observed in Fig. G-1, the effectiveness of the chemical airplanes also increases with increases in mission payload. As a consequence, the comparison results presented in Section VI will be qualitatively similar if mission payloads for all of the VLAs are increased in such a way that the average floor loadings are held constant.[a] Finally, we again note that no penalty has been assessed against the nuclear alternatives because of their split cargo compartments, even though this could be a significant consideration in actual operations.

To complete our discussion of the nuclear airplanes, we should mention their fuel consumption during loiter (for comparison with Table G-1). The VLA-NUC's is 1830 MMBtu/hr (nuclear fuel only), the VLA-NUC*'s 1330 MMBtu/hr.

COMPLETE MISSION ANALYSIS RESULTS

The following tables complement the detailed results of the station-keeping mission analysis presented in Section VIII. The mission parameters represented in each table are

		Station Radius	Minimum Time-on-Station
Table G-2a		0	12 hr
Table G-2b		0	324 hr
Table 22	Section VIII	1500 n mi	12 hr
Table 23	Section VIII	1500 n mi	324 hr
Table G-3a		3000 n mi	12 hr
Table G-3b		3000 n mi	324 hr
Table G-4a		4500 n mi	12 hr
Table G-4b		4500 n mi	324 hr
Table G-5a		6000 n mi	12 hr
Table G-5b		6000 n mi	324 hr

[a]Keeping the average floor loadings constant appears to us to be the only reasorable way to make such comparisons.

Table G-2a

STATION-KEEPING MISSIONS
ZERO N MI STATION RADIUS - 12-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	112	112	112	112	112	112	112
Carrier UTE rate	12.3	12.4	12.4	12.4	12.4	12.4	12.4
UE tankers	21	0	0	0	0	0	0
Tanker UTE rate	5.8	0	0	0	0	0	0
Average OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	11.7	12.4	12.4	12.4	12.4	12.4	12.4
Costs (billions 1975 $)							
Acquisition	4.77	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous air-borne alert)	62.42	59.28	72.34	95.00	78.72	100.10	97.18
Energy (Quads)							
Aircraft manufacture	0.09	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous air-borne alert)	14.37	11.81	14.30	16.87	29.63	17.70	37.34
Capability							
Time-on-station (hrs)	15	16	16	16	16	16	16
Avg UE on-station	102	56	56	57	56	49	98
Payload-on-station (tons)	10,181	9,868	9,874	9,889	9,875	10,676	11,241
Cost-Effectiveness ($ bil/kiloton)	6.600	6.655	8.016	10.180	9.714	9.941	10.520
Energy-Effectiveness (Quads/kiloton)	1.420	1.209	1.461	1.720	3.039	1.668	3.364

Table G-2b

STATION-KEEPING MISSIONS
ZERO N MI STATION RADIUS - 324-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	184	98	98	101	102	88	194
Carrier UTE rate	13.8	13.8	13.8	13.8	13.8	13.8	13.8
UE tankers	41	14	14	11	0	8	0
Tanker UTE rate	5.8	5.8	5.8	5.8	0	5.8	0
Average OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	12.3	12.8	12.8	13.0	13.8	13.1	13.8
Costs (billions 1975 $)							
Acquisition	4.77	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous airborne alert)	65.17	60.97	74.44	99.29	86.40	105.39	106.51
Energy (Quads)							
Aircraft manufacture	0.09	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous airborne alert)	15.12	12.19	14.77	17.69	32.98	18.70	41.56
Capability							
Time-on-station (hrs)	331	333	326	326	336	327	336
Avg UE on-station	106	56	56	58	65	51	112
Payload-on-station (tons)	10,595	9,875	9,874	10,176	11,288	11,147	12,848
Cost-Effectiveness ($ bil/kiloton)	6.601	6.821	8.229	10.300	9.179	9.996	9.931
Energy-Effectiveness (Quads/kiloton)	1.436	1.246	1.509	1.749	2.955	1.687	3.272

Table G-3a

STATION-KEEPING MISSIONS
3000 N MI STATION RADIUS - 12-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	83	59	70	76	112	71	194
Carrier UTE rate	12.9	13.2	12.9	13.2	13.1	13.1	13.1
UE tankers	142	53	42	36	0	25	0
Tanker UTE rate	11.8	12.3	12.3	12.3	0	12.3	0
Average OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	12.2	12.8	12.7	12.9	13.1	12.9	13.1
Costs (billions 1975 $)							
Acquisition	4.77	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous airborne alert)	64.71	60.97	73.91	98.58	82.56	103.88	101.84
Energy (Quads)							
Aircraft manufacture	0.09	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous airborne alert)	15.00	12.19	14.65	17.65	31.31	18.42	39.45
Capability							
Time-on-station (hrs)	12	23	12	20	16	17	16
Avg UE on-station	21	20	18	25	32	21	56
Payload-on-station (tons)	2,103	3,521	3,091	4,307	5,675	4,701	6,460
Cost-Effectiveness ($ bil/kiloton)	33.038	19.131	26.11	24.17	17.58	23.38	19.03
Energy-Effectiveness (Quads/kiloton)	7.175	3.496	4.782	4.103	5.584	3.942	6.181

Table G-3b

STATION-KEEPING MISSIONS
3000 N MI STATION RADIUS - 324-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	54	45	45	61	112	58	194
Carrier UTE rate	13.8	13.8	13.8	13.8	13.8	13.8	13.8
UE tankers	171	67	67	51	0	38	0
Tanker UTE rate	12.0	12.3	12.3	12.3	0	12.3	0
Average OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	12.4	12.9	12.9	13.1	13.8	13.2	13.8
Costs (billions 1975 $)							
Acquisition	4.77	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous airborne alert)	65.77	61.40	74.98	100.13	86.40	106.20	106.51
Energy (Quads)							
Aircraft manufacture	0.09	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous airborne alert)	15.28	12.29	14.88	17.85	32.98	18.85	41.56
Capability							
Time-on-station (hrs)	331	328	324	327	336	330	336
Avg UE on-station	30	25	25	34	62	32	107
Payload-on-station (tons)	2,990	4,355	4,352	5,902	10,850	7,057	12,350
Cost-Effectiveness ($ bil/kiloton)	23.52	15.57	18.79	17.90	9.55	15.90	10.33
Energy-Effectiveness (Quads/kiloton)	5.125	2.850	3.449	3.043	3.075	2.687	3.404

Table G-4a

STATION-KEEPING MISSIONS
4500 N MI STATION RADIUS - 12-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	54	45	54	56	112	46	194
Carrier UTE rate	13.1	13.2	13.1	13.2	13.2	13.2	13.2
UE tankers	171	67	58	56	0	50	0
Tanker UTE rate	12.2	12.5	12.4	12.7	0	12.7	0
Average OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	12.4	12.8	12.7	13.0	13.2	12.9	13.2
Costs (billions 1975 $)							
Acquisition	4.77	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous airborne alert)	65.62	60.97	74.11	98.93	83.11	104.18	102.51
Energy (Quads)							
Aircraft manufacture	0.09	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous airborne alert)	15.24	12.19	14.69	17.62	31.55	18.47	39.75
Capability							
Time-on-station (hrs)	12	18	12	12	16	12	16
Avg UE on-station	12	11	11	14	27	12	43
Payload-on-station (tons)	1,205	1,983	1,928	2,455	4,680	2,605	4,981
Cost-Effectiveness ($ bil/kiloton)	58.41	33.97	38.44	42.55	21.44	42.31	24.81
Energy-Effectiveness (Quads/kiloton)	12.721	6.208	7.687	7.222	6.823	7.132	8.077

Table G-4b

STATION-KEEPING MISSIONS
4500 N MI STATION RADIUS - 324-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	31	30	30	46	112	39	194
Carrier UTE rate	13.8	13.8	13.8	13.8	13.8	13.8	13.8
UE tankers	194	82	82	66	0	57	0
Tanker UTE rate	12.3	12.6	12.6	12.6	0	12.6	0
Average OR rate	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	12.5	12.9	12.9	13.1	13.8	13.1	13.8
Costs (billions 1975 $)							
Acquisition	4.77	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous airborne alert)	66.10	61.48	75.07	99.95	86.40	105.30	106.51
Energy (Quads)							
Aircraft manufacture	0.09	0.12	0.13	0.11	0.38	0.11	0.42
20 years' fuel (continuous airborne alert)	15.37	12.30	14.90	17.82	32.09	18.68	41.56
Capability							
Time-on-station (hrs)	324	324	328	325	336	324	336
Avg UE on-station	17	16	16	24	61	21	105
Payload-on-station (tons)	1,730	2,844	2,846	4,200	10,644	4,690	12,115
Cost-Effectiveness ($ bil/kiloton)	40.97	23.86	28.77	25.11	9.73	23.74	10.53
Energy-Effectiveness (Quads/kiloton)	8.884	4.325	5.281	4.269	3.134	4.006	3.470

Table G-5a

STATION-KEEPING MISSIONS
6000 N MI STATION RADIUS - 12-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	a	41	41	45	112	43	194
Carrier UTE rate	a	13.3	13.3	13.4	13.3	13.3	13.3
UE tankers	a	71	71	67	0	53	0
Tanker UTE rate	a	12.5	12.6	12.8	0	12.9	0
Average OR rate	a	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	a	12.8	12.9	13.0	13.3	13.1	13.3
Costs (billions 1975 $)							
Acquisition	a	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous airborne alert)	a	60.94	74.73	99.58	83.66	105.23	103.18
Energy (Quads)							
Aircraft manufacture	a	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous airborne alert)	a	12.18	14.83	17.75	31.79	18.67	40.05
Capability							
Time-on-station (hrs)	a	12	13	21	16	15	16
Avg UE on-station	a	7	7	11	23	8	39
Payload-on-station (tons)	a	1,208	1,235	1,875	3,981	1,827	4,531
Cost-Effectiveness ($ bil/kiloton)	a	55.74	66.02	56.05	25.34	60.90	27.42
Energy-Effectiveness (Quads/kiloton)	a	10.182	12.113	9.525	8.081	10.279	8.945

[a]Unable to fly this mission.

Table G-5b

STATION-KEEPING MISSIONS
6000 N MI STATION RADIUS - 324-HOUR MINIMUM TIME-ON-STATION

Mission Parameter	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Operational							
UE carriers	a	20	21	31	112	32	194
Carrier UTE rate	a	13.8	13.8	13.8	13.8	13.8	13.8
UE tankers	a	92	91	81	0	64	0
Tanker UTE rate	a	12.7	12.7	12.9	0	12.9	0
Average OR rate	a	0.58	0.58	0.58	0.58	0.58	0.58
Average UTE rate	a	12.9	12.9	13.1	13.8	13.2	13.8
Costs (billions 1975 $)							
Acquisition	a	6.39	6.81	5.52	17.21	6.03	21.08
20-year O&S (continuous air-borne alert)	a	61.38	74.94	100.35	86.40	106.15	106.51
Energy (Quads)							
Aircraft manufacture	a	0.12	0.13	0.11	0.38	0.11	0.48
20 years' fuel (continuous air-borne alert)	a	12.28	14.88	17.89	32.98	18.84	41.56
Capability							
Time-on-station (hrs)	a	329	329	327	336	325	336
Avg UE on-station	a	11	11	16	60	17	103
Payload-on-station (tons)	a	1,862	1,955	2,855	10,446	3,741	11,889
Cost-Effectiveness ($ bil/kiloton)	a	36.40	41.82	37.08	9.92	29.99	10.73
Energy-Effectiveness (Quads/kiloton)	a	6.660	7.678	6.305	3.194	5.065	3.536

[a] Unable to fly this mission.

The reader is referred to Section VIII for a discussion of line entries in these tables.

Several interesting observations can be made about Tables G-2 through G-5. For example, the superior performance characteristics of the hydrogen-fueled airplanes with in-flight refueling is reflected in the larger fraction of available aircraft able to serve as carriers. This effect is accentuated as the station radius is increased. Despite this performance advantage, neither the VLA-LH_2 nor VLA-LH_2* alternatives is particularly attractive; this is because the two airplanes have substantial O&S costs--attributable largely to the unit energy costs of liquid hydrogen.

Also interesting is a comparison of the costs of the VLA-JP and VLA-NUC alternatives. Note that the nuclear airplanes' acquisition costs are almost three times greater than the VLA-JP's. Perhaps surprisingly, the O&S costs are also larger for the VLA-NUC (see Appendixes D and E).

Finally, we should note that the C-5B might be able to fly the 6000 n mi station radius mission (Tables G-5a and b) if more complex operational flight profiles had been considered. Almost certainly, though, the C-5B would not be attractive in terms of cost-effectiveness or energy-effectiveness for such extreme station radii.

Appendix H

SOME AUXILIARY ISSUES

Auxiliary issues examined in this appendix have been classified as either military-related or public-policy-related. The latter category includes considerations which may have little bearing on the military worth of the weapon system but which could greatly affect the public's perception of the acceptability of the system. We shall first discuss relevant issues in each classification and then present a summary comparison which displays the relative attractiveness of all seven alternatives for each issue examined.

MILITARY-RELATED ISSUES

We have identified seven issues which bear on the military utility of very large airplanes. These are

- Technical risk
- Basing flexibility
- Routing flexibility
- In-flight vulnerability
- Pre-launch survivability
- Development potential
- Crew safety

Most of the seven are of concern to both the strategic airlift and the station-keeping applications. When an issue is of particular importance to a specific type of mission, we shall so note.

Technical Risk

Technical risk is important since the time frame in which each of the alternatives might be available depends on the research and development effort it requires. In addition, alternatives that embody substantial technical risk are especially likely to encounter unforeseen costs as the development program proceeds.

Without doubt, the nuclear-powered airplanes represent the highest-risk alternatives. Much of the risk is concentrated in the very significant research and development required by the nuclear reactor system (including heat exchangers) [10,25,111]. Indeed, a recent review of the state of the art of lightweight nuclear reactor technology has indicated that a clear choice between the two most promising reactor concepts (liquid-metal reactors, of the type employed in our analysis, and gas-cooled reactors) is not at present possible [112]. The risk is further accentuated by nuclear airplanes' having much larger gross weights than other VLAs; concomitant with these larger gross weights is the implication that the nuclear airplanes will require more advanced airframe technology [23].

Conversely, the C-5B is clearly the least risky alternative. Furthermore, if the wing modification of the existing C-5A fleet proceeds as scheduled [49], the technical risk associated with C-5B acquisition would be still further reduced. (Modified versions of other contemporary airplanes would probably have similar attributes in this regard.)

In our view, the JP- and cryogenic-fueled alternatives represent comparable levels of technical risk. Several major airframe manufacturers have recently developed conceptual designs for liquid-hydrogen-fueled aircraft [63,113,114], some of which are fairly detailed [21,115]. The consensus appears to be that the principal technical impediment to LH_2 as a fuel is the development of the cryogenic-fuel subsystem. Such problems, which are largely associated with identifying suitable insulation (for on-board storage tanks, etc.), seem solvable through advanced development.

These difficulties with the liquid-hydrogen alternatives could be largely balanced by the VLA-JP's greater maximum gross weight. Finally, although the VLA-LCH_4 is comparable to the VLA-JP in gross weight, its fuel subsystem should present less of a problem than the VLA-LH_2's because liquid methane has more favorable cryogenic properties.

Basing Flexibility

This issue is included to reflect the compatibility of each alternative with existing airfields. (It is of primary interest to the

airlift application; most station-keeping missions can presume the use of specialized fields, if they are required.) The cryogenic-fueled airplanes and the nuclear airplanes are probably the most inflexible in this regard--but for different reasons. The cryogenic-fueled airplanes require specialized ground refueling facilities and we believe it imprudent to assume that such facilities would be widely available throughout the world by the end of the century. This would be particularly true if the USAF were the only operator of cryogenic-fueled airplanes; if liquid hydrogen came into widespread use for commercial aviation, the situation would be improved [40,41]--but we think this unlikely.

Nuclear airplanes, on the other hand, may be prohibited from operating above most land masses with their reactors in operation. Such a restriction could lead to their being based solely in coastal areas, and this would greatly limit their flexibility. Even if land overflights were permitted, however, the extreme gross weights of the nuclear-powered alternatives might preclude the use of many existing airfields (depending, of course, on the alighting system employed).

The C-5B would be the most flexible in terms of the number of suitable airfields available to it. This alternative would probably be the least objectional in terms of landing gear footprint pressure and certainly imposes the least total burden on the runway's ultimate capacity.

We think the VLA-JP is less attractive--though only slightly less attractive--than the C-5B in this regard because of its greater maximum gross weight and physical dimensions. Its dimensions could restrict (or hamper) its use at some fields because of interference with existing surface structures or incompatibility with taxiways, etc.

Routing Flexibility

Another operational consideration concerns flexibility in route selection. Here, we are primarily interested in the airplane's ability to fly routes that are compatible with restrictions on overflight rights. Such restrictions could either be politically imposed, as in the 1973 Middle East war (see Section I), or arise from a desire to avoid particularly high-threat areas.

The nuclear airplanes, because of their essentially unlimited range capability, appear to be the most flexible. They could operate without the benefit of any overseas refueling bases and they eliminate the need that the other alternatives have for at least one base in the Western Pacific (as discussed in Sections VII and VIII). Furthermore, they could be easily routed to avoid territory where overflight restrictions might be imposed and yet incur no performance penalty (i.e., reduced payload) in so doing.

The cryogenic-fueled airplanes represent the other extreme--for two reasons. First, as mentioned in the discussion of basing flexibility, the planning of their operations must always be cognizant of which bases can be used for ground refueling. More importantly, perhaps, is the marked loss in payload capability that might occur for the liquid-hydrogen and liquid-methane alternatives if the mission leg is slightly lengthened to avoid overflights. For example, if the flight distance were increased from 6000 n mi to 7000 n mi, the payload capability would be reduced by about 36 percent for both the VLA-LH_2 and the VLA-LCH_4; the corresponding VLA-JP payload reduction is only about 18 percent (see Fig. 10). Because of its substantially inferior range capability, we feel that the C-5B should also be considered unattractive in terms of routing flexibility.

The VLA-JP has middling characteristics in this regard. It is clearly superior to the cryogenic alternatives and the C-5B, but it cannot approach the inherent routing flexibility of the nuclear airplanes.

In-Flight Vulnerability

In-flight vulnerability involves the airplane's susceptibility to hostile actions. Included are the ability of the airplane to avoid detection and to sustain battle damage.

From an overall viewpoint, we feel that the cryogenic-fueled airplanes would be the most vulnerable. They have the largest radar cross-sections--particularly the LH_2-fueled alternatives. However, the combustion characteristics of hydrogen-burning engines might significantly reduce the engine's infrared signature [116,117] and probably

make the cryogenic-fueled airplanes no easier to detect than the other VLAs.

In our view, however, the Achilles' heels of the cryogenic-fueled airplane is the vulnerability of its fuel tanks.[a] A recent study [118] concluded that an LH_2 aircraft's vulnerability is greater than that of a JP-fueled airplane because:

- o The fuel tanks are required to operate at pressures above atmospheric pressure.
- o A failure of the thermal protection system of the fuel storage and distribution systems can create hazards associated with excessive internal pressures and the formation of liquid air, rich in oxygen.
- o Hydrogen is flammable over a wide range of fuel/air mixtures and can be easily ignited (see Table 3).

This is *not* to suggest that the explosive detonation of the liquid-hydrogen is the principal problem. Indeed, the limited available test data [119] indicate that the penetration of liquid-hydrogen fuel tanks by incendiary projectiles results in less of an explosive conflagration than that exhibited by tanks containing JP-4.[b] Rather, the vulnerability is largely associated with the fuel's thermal-protection system. Even though recent work has suggested that cryogenic fuel tanks can be designed to minimize the likelihood of penetration [120, 121], it nonetheless appears to us that the cryogenic fuel system remains significantly more vulnerable than a corresponding JP fuel system.

We have judged the VLA-JP and the nuclear airplanes to have the most favorable vulnerability characteristics but, again, for different reasons. The infrared signatures of nuclear airplanes will be

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[a]This discussion is mainly based on studies investigating liquid hydrogen as a fuel. Although the corresponding aspects of using liquid methane will probably be somewhat less troublesome, we believe that the problems are of comparable magnitudes.

[b]The physical properties of JP-8 (Jet-A) are substantially different, but JP-8 has not been included in these experiments.

substantially less than those of the VLA-JP; however, this could be largely balanced by their greater radar cross section.

We feel that there is very little difference between the nuclear and VLA-JP airplanes in their ability to withstand battle damage. A possible exception stems from the location of the engines of the VLA-NUC and VLA-NUC* (see Appendix A). Conceivably, all eight engines could be rendered inoperable by a single hit, which, in the case of the VLA-JP, might disable only one engine. Furthermore, the NaK coolant would burn on exposure to air, thus increasing the potential danger from battle damage to the heat exchangers or coolant lines.

These three alternatives have the capability to loiter for extended periods. However, the VLA-JP's tanker support may be vulnerable, since the tanker must fly to the loiterer at high altitudes (above 25,000 ft) to take full advantage of the VLA-JP performance capability. On the other hand, the nuclear-powered alternatives are essentially single-engined airplanes. We feel that the possibility of reactor shutdown balances the vulnerability of the VLA-JP's tanker support.

Finally, the C-5B (despite its smaller radar cross section) appears to us to be slightly inferior to the VLA-JP or the nuclear airplanes in terms of in-flight vulnerability. This conclusion is based principally on the lesser range and endurance capabilities of this contemporary airplane. For the strategic airlift mission, its limited range might prevent in-flight rerouting to avoid hostile actions; in the station-keeping missions, its vulnerability is increased by the greater amount of tanker support it needs compared to the VLA-JP (for a given mission profile, the C-5B generally requires more tanker sorties). Note, however, that the loss of a single C-5B would be of less importance than the loss of a VLA, since for a given capability level, many more C-5Bs are required.

Pre-Launch Survivability

Pre-launch survivability is of principal interest in the station-keeping missions. It refers to the ability of an airplane (usually being maintained on a ground-alert status) to taxi, take off, and

depart the area immediately upon warning that the airbase is under attack. (These characteristics might also be important if the APOD in a strategic airlift scenario were attacked.) The figures-of-merit in this instance are the elapsed time from warning until the aircraft is a safe distance from the airfield and the nuclear hardness of the aircraft. If the threat consists of nuclear-armed ballistic missiles (particularly sea-launched missiles employing depressed trajectories), differences in elapsed time of as little as tens of seconds are important. We see no reason to suppose that any of the alternatives would have significantly different nuclear hardness and will therefore concentrate on the elapsed time (from warning to escape).

The liquid-hydrogen-fueled alternatives appear to possess the least suitable pre-launch survivability characteristics. When the alternative is maintained on a ground-alert status, provisions must be made for periodic replenishment of the liquid hydrogen that is inevitably lost due to boil-off. (Whether or not the gaseous hydrogen is recovered is not important to this issue.) Such added complexity, even though relatively modest, may be sufficient to increase slightly the average expected warning-to-escape elapsed time.[a] Associated aircraft losses in the event of an attack might be significant.

For the same reason, we believe the VLA-LCH_4 would be somewhat less survivable than the JP- and nuclear-fueled alternatives. However, the problem should be of lesser magnitude than for the LH_2-fueled alternatives.

The alternatives employing JP for takeoff, climbout, etc. (the C-5B, VLA-JP, and both nuclear airplanes) are thus thought to have a pre-launch survivability superior to that of the cryogenic-fueled airplanes. However, we have been unable to identify any differences in these four alternatives.[b]

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[a]Note that the taxi, takeoff, and climbout times should be comparable since all alternatives require the same takeoff distance at maximum gross weight.

[b]Several hours would be required to melt the NaK coolant used in the nuclear airplanes if it were to solidify. However, if the reactor is operated at full power as infrequently as once per month, the afterheat should be sufficient to maintain the coolant in a liquid state.

Development Potential

With this issue we are attempting to identify which alternatives would most benefit from unforeseen technological developments.[a] In this instance, the greatest potential for improvement probably accrues to the nuclear-powered airplanes. Specifically, if, while still maintaining crash integrity, reactor-system weight (including the containment vessel) could be substantially reduced as the result of a breakthrough, the attractiveness of the nuclear airplanes would be enormously enhanced.

Similarly, the alternatives using liquid hydrogen could be much more attractive in terms of cost and energy if a breakthrough occurred in the hydrogen-production process. (An obvious example is coupling a fusion reactor with a thermochemical watersplitting cycle, but neither of these technologies has yet been demonstrated on a laboratory scale.) We have judged the liquid-hydrogen and nuclear-fueled alternatives as comparable in regard to their development potential.

At the other extreme is the C-5B which would benefit little, if at all, from new technologies.

The remaining alternatives, the VLA-JP and VLA-LCH_4, are thought to have a development potential between these extremes. (Here we are assuming that the hydrogen-production process offers a richer menu of possibilities for advances in technology than the methane- or JP-synthesis processes.)

Observe that the preceding discussion has largely concentrated on the fuels. Except for the already designed C-5B, unforeseen advances in aircraft technology would tend to benefit to some extent all of the alternatives, although the VLA-JP is likely to be the greatest beneficiary, as discussed in Section IX.

Crew Safety

The final military-related issue is crew safety--the safety of ground crews as well as flight crews. Because of the potential dangers

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[a]How foreseeable developments in technology affect the alternatives is explicitly addressed in Section IX.

from cryogenic fuel spills or leaks (e.g., as the result of the rupture of fuel tanks or lines), we believe these alternatives pose the greatest safety hazard. We are less concerned with the possibility of the liquid cryogen detonating than with the effect of exposure to the low temperatures associated with these fuels in the liquid state.[a] In addition, liquid hydrogen which vaporizes quickly after exposure to ambient temperatures could form an explosive hydrogen/air mixture. This is only likely to occur, however, if the hydrogen gas is allowed to collect within a confined volume; without confinement, gaseous hydrogen diffuses rapidly [123].

In terms of crew safety, the C-5B and VLA-JP are thought to be most attractive. Clearly, they represent the least deviation from today's practices.

As for the flight crew's safety, the nuclear airplanes, the C-5B, and the VLA-JP should be comparable. However, the ground handling of nuclear fuels does pose difficulties not present in the JP cases. But there should be fewer safety problems with nuclear airplanes than with the cryogenic-fueled airplanes, since the reactor fuel would be exposed to ground personnel only infrequently.

PUBLIC-POLICY-RELATED ISSUES

Numerous auxiliary issues exist that, heretofore, have not generally been considered in the evaluation of alternative weapon systems. These include:

- Public safety
- Air pollution
- Noise pollution
- Energy-resource depletion
- Water-resource depletion
- Land-use impact

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[a]We should note, however, that no such accidents have ever occurred at the NASA facilities at Cape Canaveral [122]. Whether such a safety record could be maintained in routine handling by Air Force ground crews is an open question.

An increased perception of the importance of such issues by the public may require that these aspects be examined more fully in the future. Each issue is discussed below in the context of the seven alternative airplanes.

Public Safety

Of all these policy issues, public safety is perhaps the most important and almost certainly would receive the greatest attention. Of course, the safety issue surfaces primarily because of the problems (some real, some imagined) associated with nuclear propulsion for aircraft. Indeed the importance of this topic has caused us to include a preliminary exploration of the unique aspects of nuclear-powered airplanes in Appendix I.

In our view, the most serious safety problem facing nuclear airplanes is the potential release of harmful radioactive substances as a result of rupturing the containment vessel in a crash. Based on the relatively meager information presently available, it appears that the probability of such a release can be made quite small through the application of appropriate design constraints. However, the damage that could result should this unlikely event occur is enormous. Therefore, nuclear-powered airplanes are thought to present the greatest potential public safety problem. (See Appendix I for an extended discussion.)

Perhaps surprisingly, we have judged the cryogenic-fueled airplanes as most attractive in terms of public safety for the following reasons. First, we assume that the probability of a crash in a populated area is the same for all chemical-fueled airplanes; the public safety questions are thus concerned with post-crash effects. For the liquid-hydrogen alternatives, fuel spewing from ruptured fuel tanks will quickly vaporize; the gaseous hydrogen (as noted previously) should quickly diffuse. Thus the possibility of an explosive conflagration is almost nonexistent [123]. Should the gaseous hydrogen ignite, the flame is of extremely low emissivity and this significantly reduces the amount of radiated heat [120]. All told, the fire damage to the immediate crash area could be substantially less than from a comparable jet-fuel fire.

Assessing such dangers for the VLA-LCH_4 alternative is less certain. Methane's greater density causes it to diffuse less rapidly [124], but it may be less likely to ignite than hydrogen. We assume these two effects balance each other, and therefore regard the cryogenic-fueled airplanes as equivalent in terms of public safety.

The two JP-fueled airplanes are judged to lie between the cryogenic and nuclear alternatives.

Air Pollution

Without a doubt, airplanes fueled with liquid hydrogen have the most favorable air pollution impacts. The absence of carbon eliminates carbon monoxide and incomplete hydrocarbon combustion products in the exhaust emissions. Limited experimental data also suggest that emissions of nitrogen oxides will be substantially less than those of a comparable conventional jet-fuel engine [21,117]. (The maximum ceiling of all seven alternatives precludes their water vapor and nitrogen oxides emissions having any effect on the ozone layer [125].)

Little is known regarding the emission characteristics of methane-fueled turbine engines. With internal combustion engines, however, methane results in significantly reduced emissions--particularly of carbon monoxide and unburned hydrocarbons--compared to gasoline. Thus, we believe the air pollution characteristics of the VLA-LCH_4 would be superior to those of airplanes using JP but less impressive than those using LH_2.

The C-5B, VLA-JP, and nuclear-powered airplanes will have comparable air quality impacts. Including the nuclear airplanes in the same category as those using conventional jet fuel may seem unwarranted. However, the principal effects of aircraft emissions occur in the vicinity of the airfield [126,127]. Since the nuclear airplanes take off and land with the engines operating in the JP-mode (see Appendix A), they offer no advantage with respect to reduced emissions. Indeed, the nuclear alternatives may even be somewhat worse since both of them employ eight engines compared to the six on the VLA-JP.

Noise Pollution

Assessing the relative noise pollution ranking of the alternatives is less straightforward. Table H-1 presents an illustrative comparison

Table H-1

NOISE COMPARISON OF LH_2 AND JP-FUELED AIRPLANES

Aircraft Design	Noise Levels (EPNdB)[a]			Area of 90 EPNdB Contour (sq mi)
	Flyover	Sideline	Approach	
Medium-range				
LH_2	88.7	86.8	94.5	1.71
JP	90.7	86.8	94.5	1.96
Long-range				
LH_2	92.7	87.8	96.4	2.72
JP	95.1	88.3	95.4	3.25

SOURCE: Lockheed-California Co. [21].

[a]Effective perceived noise level.

of the noise characteristics of aircraft fueled with either LH_2 or JP and designed for the same mission. Note that the liquid-hydrogen-fueled airplanes display a somewhat smaller noise footprint, despite their higher noise levels on approach. In view of this result, we feel that the VLA-LH_2 would have the most favorable noise characteristics of all the very large airplane alternatives. However, the C-5B is substantially lighter and its four engines provide much less total thrust than those of the other VLAs. Hence, we have assumed that the C-5B (even though representing an older technology) and the VLA-LH_2 are comparable in terms of noise.

The noisiest of the seven alternatives would probably be the VLA-NUC, because of its significantly greater gross weights and total engine thrust. Also, the bypass ratio of the dual-mode nuclear engines is only 3.85 compared to 10 for the chemical-fueled VLAs. However, the resulting increased noise levels could be partially masked from the ground by the location of the engines in the nuclear airplanes.

The remaining four alternatives all have comparable maximum gross weights and total thrust levels. Accordingly, we have judged them all to have intermediate noise impacts, between the VLA-LH_2 and the VLA-NUC. Clearly, such a judgment should only be regarded as a first approximation. The more detailed analysis required to differentiate among alternatives, however, does not seem warranted for our present purposes.

Energy-Resource Depletion

This issue was extensively discussed in Section VI. To summarize the energy-resource-depletion characteristics of the alternatives, the VLA-JP, C-5B, and VLA-LCH_4 alternatives appeared most attractive. However, the liquid hydrogen-fueled airplanes were somewhat greater consumers of the available coal resource base. Depending on whether or not the liquid-metal fast breeder reactor becomes a commercial reality (within the appropriate time frame), the nuclear airplanes were among the most attractive or the least attractive alternatives.

Water-Resource Depletion

Evaluating the alternatives' depletion of water resources is fraught with similar technology-dependent uncertainties. Beyond question, the two nuclear airplanes are most attractive in this regard since the nuclear fuel cycle consumes little water. (Of course, we are assuming that the long-term storage of radioactive wastes is developed to the point that the leaking of such wastes to the water table would be essentially impossible.)

The supply processes for all of the chemical fuels (when synthesized from coal), however, consume enormous amounts of water [19]. Indeed, the water supply problem may be of paramount importance to coal conversion facilities located in the Rocky Mountain west. In our view, the water-resource depletion potential of all the chemical-fueled airplanes is equally unattractive. (See Ref. 19 for a fuller discussion.)

The airplanes fueled with liquid hydrogen offer possibilities that might alleviate the water supply problem. Specifically, if an advanced thermochemical water splitting process were available for hydrogen production, the water resource depletion could be greatly relieved. Of

course, much of the relief is provided by assuming the production facility is located near abundant water supplies (possibly even using sea water). In these circumstances, the LH_2 airplanes could be as benign as their nuclear-powered counterparts with respect to water resources.

Land-Use Impact

In terms of their land-use implications, we have judged all of the alternatives to have a middling impact. Mining of the coal for the chemical fuels--either with strip or deep mining--will have significant impacts in terms of the number of acres affected. However, the reclamation policy as well as the type and location of the mine greatly influences the duration of this impact [19].

We feel that the land-use consequences of mining could be largely balanced by the adverse implications associated with the long-term storage of high-level radioactive wastes. Conceptually, mining operations might impact 100,000 acres for 10 years whereas nuclear waste storage might only impact 10 acres but for 100,000 years. Deciding which of these hypothetical situations is more onerous is well beyond the scope of the present work.

SUMMARY COMPARISON

The observations and judgments made in the preceding discussion are summarized in Table H-2. Here, the relative attractiveness of the alternatives for each issue is presented using a technique similar to that employed in our earlier comparisons of cost-effectiveness and energy-effectiveness. For each issue, the alternatives with the most attractive attributes, those with the least attractive, and those with attributes in the middle of the range are indicated. As noted in the earlier discussion, how the alternatives compare in terms of energy- or water-resource depletion is dependent on essentially unrelated technological developments; this uncertainty is so indicated in Table H-2.

An additional issue, the perceived threat value, has been included in Table H-2. By this we attempt to assess the threat which potential

Table H-2

RELATIVE ATTRACTIVENESS OF THE ALTERNATIVES IN TERMS OF THE AUXILIARY ISSUES

Issue	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC	VLA-LH_2*	VLA-NUC*
Technical risk	Most attractive	Intermediate	Intermediate	Intermediate	Least attractive	Intermediate	Least attractive
Basing flexibility	Most attractive	Intermediate	Least attractive	Least attractive	Least attractive	Least attractive	Least attractive
Routing flexibility	Least attractive	Intermediate	Least attractive	Least attractive	Most attractive	Least attractive	Most attractive
In-flight vulnerability	Intermediate	Most attractive	Least attractive	Least attractive	Most attractive	Least attractive	Most attractive
Pre-launch survivability	Most attractive	Most attractive	Intermediate	Least attractive	Most attractive	Least attractive	Most attractive
Development potential	Least attractive	Intermediate	Intermediate	Most attractive	Most attractive	Most attractive	Most attractive
Crew safety	Most attractive	Most attractive	Least attractive	Least attractive	Intermediate	Least attractive	Intermediate
Public safety	Intermediate	Intermediate	Most attractive	Most attractive	Least attractive	Most attractive	Least attractive
Air pollution	Least attractive	Least attractive	Intermediate	Most attractive	Least attractive	Most attractive	Least attractive
Noise pollution	Most attractive	Intermediate	Intermediate	Most attractive	Least attractive	Intermediate	Intermediate
Energy resource depletion	Most attractive	Most attractive	Most attractive	Intermediate	Most attractive (with diagonal)	Intermediate	Most attractive (with diagonal)
Water resource depletion	Least attractive	Least attractive	Least attractive	Most attractive (with diagonal)	Most attractive	Most attractive (with diagonal)	Most attractive
Land-use impact	Intermediate	Intermediate	Intermediate	Intermediate	Intermediate	Intermediate	Intermediate
Perceived threat value	Least attractive	Intermediate	Intermediate	Intermediate	Most attractive	Intermediate	Most attractive

Most attractive   Intermediate   Least attractive

enemies would perceive in each of the alternatives. We suggest that a weapon system should be regarded attractive if it would require potential enemies to consider a significant reallocation of resources in order to provide an acceptable defense or, alternatively, to neutralize the deterrence value of the weapons system.

It is our belief that the nuclear airplanes would provide the greatest perceived threat. Their inherent operational flexibility (which may include operating concepts that are not presently apparent) and their ability to remain airborne for extremely long periods without relying on ground-based resources would make defense against them difficult. The C-5B, we believe, has the least perceived threat value, since it is only a derivative of an airplane that exists today. The other very large airplanes should provide a perceived threat somewhere in the middle of this range.

To select the alternative that from an overall viewpoint is most attractive, one must attach some relative importance to each of the auxiliary issues. It is our view that it would be difficult to rgue that any of the alternatives is significantly more attractive than the VLA-JP. Such a conclusion is particularly strengthened by the cost-effectiveness and energy-effectiveness characteristics presented earlier.

Before concluding, a comment on the validity of the assessment summarized in Table H-2 seems appropriate. Two aspects of this analysis are important--the reasonableness of the judgments made in assessing each issue and the completeness of the list of issues. We hoped to minimize misjudgments and omissions from the list by briefing these study results to a wide variety of organizations both within and outside the Air Force.[a] Exposing the qualitative assessments to many individuals with different backgrounds and viewpoints stimulated dialogues on many of the individual issues. Indeed, this section includes much that was derived from these dialogues.

Nonetheless we have less confidence in the results discussed in this appendix than we have in the quantitative comparisons of the alternatives presented in the main text.

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[a]Briefings have been presented at the following headquarters: Military Airlift Command, Strategic Air Command, Tactical Air Command, and Systems Command. Other organizations briefed include the USAF Aeronautical Systems Division, Weapons Laboratory, and NASA Langley Research Center (Aeronautical Systems Division).

Appendix I

SAFETY AND ENVIRONMENTAL ASPECTS OF NUCLEAR-POWERED AIRPLANES

In Section IX we observed that the principal criteria for judging the relative merits of the alternatives examined in this work have been their cost- and energy-effectiveness in a variety of mission applications. We also noted that other attributes of the alternatives (e.g., vulnerability) should either be taken into account or explicitly included in the cost, energy, or effectiveness metrics. Accordingly, Appendix H presented a qualitative discussion of several such auxiliary issues. Of the issues examined, we believe that the potential safety and environmental dangers associated with nuclear-powered airplanes are the overriding concern.[a] Associated with the fear of these dangers is the possibility of domestic and/or international legal and political obstacles to this application of nuclear power.

Although the safety and environmental issues raised in this appendix would be of prime importance if the development of a nuclear-powered airplane were seriously contemplated, *significant additional research and study is probably not required until nuclear aircraft demonstrate a compelling attractiveness in terms of costs, energy consumption, or mission effectiveness.*

CLASSIFICATION OF ISSUES

The safety issues associated with nuclear-powered airplanes can be classified according to whether they primarily affect operational personnel or the general public. Assuming that the size requirements for nuclear aircraft do not impose any unique safety problems, the major safety problems are those related to the potential release of

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[a] A recent study by students at the Air Force Institute of Technology (AFIT) [10] has discussed many of these issues in some depth; liberal use of their results has been made throughout this appendix.

radioactivity. Adverse environmental effects may result from radiological or thermal pollution associated with an airborne nuclear power plant. (In this appendix, any radioactive release that does not directly affect military personnel or the public is considered as an environmental effect.)

The safety and environmental issues to be examined are illustrated in Table I-1. The matrix elements with a "✓" entry are judged to require consideration. Note that the safety of operational personnel in a crash is not checked since we are concerned with the unique problems presented by a nuclear-propulsion system. It is assumed that in crashes, the characteristics of the nuclear aircraft would not pose any important new problems for crew safety which would not be addressed when considering public safety issues for such a situation.

Table I-1

CLASSIFICATION OF NUCLEAR AIRPLANE SAFETY AND ENVIRONMENTAL ISSUES

	Safety		Environment	
	Operational Personnel	General Public	Thermal Pollution	Radiological Pollution
Routine Operation	✓	✓	?	?
Reactor Accidents				
- in-flight	✓	✓		✓
- on the ground	✓	✓		✓
Crashes		✓		✓

The available knowledge about the potential dangers associated with these issues is described below. Although some of the issues may turn out to be unimportant with respect to nuclear-powered flight--especially the environmental dangers associated with routine operation--their importance in the debate over land-based reactors suggests that these questions are likely to arise.

ROUTINE AIRCRAFT OPERATION

Crew Safety

Crew safety during routine operation can be maintained either by shielding the crew or by shielding the reactor. The design philosophy in the Aircraft Nuclear Propulsion (ANP) program of the 1950s was controlled by a severe gross-weight restriction and by lower-power-density reactors; although it included some reactor shielding, it mostly stressed flight-crew shielding. Radiation exposure for the ground crew would have been sufficiently high to require special maintenance procedures [128]. The elimination of the 500,000-lb gross weight limit on nuclear-powered aircraft designs led to a reconsideration of shielding. For these larger aircraft, the divided-shield concept was dropped and a unit-shield approach adopted [129]. Unit-shields prevent radiation levels outside the reactor shield from exceeding some relatively low level, usually the AEC[a] dosage limit for full-time radiation workers [130].

Assuming that a unit-shield design maintains exposure rates below AEC industrial standards,

- What do we know about the effects of continuous exposure to radiation for prolonged periods?

In the present work as well as in other recent investigations [10], a maximum flight duration of 14 days (336 hours) has been suggested. Rom and Finnegan mention 1000-hr exposures, but do not discuss whether there is a qualitative difference between the continuous exposures of flight crews and the interrupted exposures usually associated with the occupational doses received by industrial workers only during working hours [128]. Presumably, experience with the radiation exposure of nuclear submarine crews would be a guide in answering this question.

[a]The U.S. Atomic Energy Commission dosage limits are now the concern of the Nuclear Regulatory Commission (NRC).

Public Safety

The divided-shield concept presented major public safety problems. The public would have been protected by limiting nuclear-aircraft flights to well-defined isolated corridors [131]. The use of the unit shield provides greater public protection in both routine and emergency operations.

The type of propulsion system used can also affect public safety. In the original ANP program, direct and indirect cycle systems were considered [132]. The direct cycle's thermodynamic efficiency exceeds the indirect cycle's; however, when the air heated in a direct cycle system passes through the reactor, it can pick up fission products. This unsatisfactory safety factor has led to an emphasis on the indirect cycle [25,112] for the following reason. In practice, a small fraction of the fuel beads can be expected to fail. Such failures can be hazardous with only one heat exchanger because they would result in the release of radioactive fission products into the atmosphere; the indirect cycle, with two heat exchangers, precludes this. Therefore, any nuclear-propulsion system is likely to have the entire primary loop within the containment vessel [25]. Applying the present standards for the maximum dose rate to the general population,[a] the recent AFIT study concludes that, with present reactor technology, a reactor providing safe operation for the flight crew will not present a hazard to the general populace either from effluent or direct radiation [10].

The issue of what is a safe level of radiation dosage has yet to be settled entirely, but the resolution of the potential problems mentioned above are based on a judgment of this "safe" level. For instance, Rom uses 0.25 millirems per hour as an allowable dose level for the general population [133] instead of the annual limit mentioned in the AFIT study [10].

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[a]The standard applied to light-water reactors was used, 5 millirem per year [10].

Thermal Pollution

The in-flight thermal effects of an individual aircraft are not likely to be troublesome, but the effects of a fleet of nuclear-powered aircraft might present a problem.

Earlier, the following question was raised:

- Could some number of aircraft at an airbase create weather modifications similar to those that have been considered in connection with nuclear-power parks?

The thermal effects would be generated by the afterheat of shutdown reactors. Muehlbauer describes the highest likely afterheat power as 7 percent of the full-power rating [25]. Assuming that aircraft propulsion reactors have 300 to 500 MWt of power, each while on the ground could contribute as much as 21 to 35 MWt after full-power operation. Thus, if 100 such airplanes were at one airfield, waste heat on the order of 2000 to 3500 MWt could be rejected to the atmosphere. This load on the atmosphere would be comparable to that imposed by a 1000 MWe power plant,[a] and Koening and Bhumralkar have estimated that the atmospheric effects of a 1000 MWe plant are not significant [134].[b] Since the aircraft would create only temperature perturbations in the atmosphere and not moisture perturbations, the effects probably would be even less significant. It is also exceedingly unlikely that 100 aircraft of this size would ever be simultaneously at the same base.

Radiological Pollution

Civilian nuclear-power reactors routinely emit small amounts of radioactive gases [102]. However, monitoring by the U.S. Public Health

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[a]With a 33 percent conversion efficiency, a 1000 MWe plant rejects 2000 MWt of heat.

[b]The limited area of the atmospheric perturbation is mentioned as a contribution to the insignificance of the effects. The effect of the larger area that the aircraft would cover is not clear.

Service has indicated that they add to the environment only a minute fraction of the amount of radioactivity present naturally [135]. In the requirements Rom sets for practical, safe, and publicly acceptable nuclear aircraft, he includes "no release of radioactivity in normal operations" [134]. However, the AFIT study considers the release of radioactive effluent by using the Peach Bottom HTGR as a reference and by assuming that release would be directly proportional to the operating power level. The study concludes that the effluent radiation for a fleet of 60 aircraft would be negligible [10].

The handling of the spent fuel may present a more severe routine operational problem than the matter of radioactive effluents. Unfortunately, insufficient data on this issue are presently available. Required data would include the quantity of waste generated and the effect of the highly enriched fuel on the nuclear waste produced.

REACTOR ACCIDENT ISSUES

Here the term "reactor accidents" does not include crash situations; it is used to describe any release of radioactivity attributable to the failure of an aircraft nuclear reactor to function properly.[a] These accidents could occur either while the airplane is in flight or is on the ground.

In Flight

The safety of the flight crew appears unlikely to be endangered by a reactor accident in flight, if the airplane can land quickly and if the reactor is enclosed in a containment vessel designed to withstand a crash and a core meltdown. Such an accident might lead to an unusual situation, for it appears to be the only case where there may be a conflict between the protection of the crew and the protection of the public. The crew might need to continue flying so as to avoid landing the airplane in a populated area. This might expose the crew to

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[a] We assume that when such accidents occur, the thermal effects to the environment are unimportant.

greater radiation than they would have had if they had landed immediately, but would better protect the public.

Probability of Occurrence. The types of reactor accidents that need to be considered include the loss of coolant accident (LOCA) and accidents caused by transient events. (A transient event can be defined as a condition imposed on the reactor coolant system that results in a demand for reactor shutdown.) The AFIT study, using the estimates for pipe failure probabilities included in the recent "Reactor Safety Study" (WASH-1400) [136], asserts that the probability of a LOCA is negligible. However, this assertion could be questioned in the following ways [10]:

- o Are the WASH-1400 figures--which have been vigorously debated [53]--firm enough to be used here?
- o Even if one assumes that the figures are valid for ground-based reactors, are they valid for airborne reactors?
- o If failure probabilities do differ, are the pipes in an airborne reactor system more or less likely to fail?

Transient events can be caused by a surge in power generation or a reduction of cooling capacity. The AFIT study bases its transient event work on WASH-1400 figures, and the WASH-1400 approach is based on the historical record of ground-based power-generating systems. The questions here are:

- o Are the WASH-1400 figures valid for ground-based reactors?
- o If so, are they valid for airborne reactors?
- o If ground-based and airborne reactors differ, in what ways do they differ?

Rom and Finnegan discuss another potential in-flight accident—fuel pin leakage [126]. They conclude that, in a direct-cycle system,

even if as many as 100 fuel pin segments were to fail, the crew could still tolerate 10 hours of exposure before receiving what the Federal Radiation Council deems the maximum allowable dose level (25 rem per accident). They also assert that past experience with fuel pins indicates a "virtually zero" probability of even one fuel pin leaking [128]. The indirect cycle clearly provides even greater margins of safety in this regard.

So far, no mention has been made of how hostile actions would affect the probabilities of system failures. The question here is:

- What are the conditional probabilities of radioactivity being released given that the aircraft is attacked?

There may be no reason for an enemy to attack a nuclear-powered aircraft if to do so would result in the release of radioactivity on the enemy's own forces, but to assume this is to assume rational behavior (an heroic assumption once hostilities are under way). And the enemy could, of course, attack the nuclear-powered aircraft when only friendly forces would be exposed.

The circulation of hot fluids heated by the reactor and flowing to the engine heat exchangers also introduces dangers not present for conventionally powered aircraft, especially additional fire hazards (NaK and Li both burn upon contact with air). These, however, may be minimized by exercising judgment in the aircraft design (e.g., in where the engine is located).

Consequences. Except for the Rom and Finnegan discussion of possible crew exposure from fuel pin leakage, no data on the potential danger to the public from in-flight reactor accidents has been found. The AFIT work considers the probabilities of release from in-flight accident to be trivial compared with the probabilties of an impact-event. However, the consequences of such an in-flight accident must be considered:

- o Even though the probability of such an accident occurring is relatively small, are its likely consequences so great that the expected value of the damage is of enormous importance (i.e., the zero-infinity dilemma)?

On the Ground

Although this may not be an important class of accidents, mention must be made of some potential problems that might result from accidents to nuclear airplanes on the ground.

Probability of Occurrence. No data have been found that deal with this issue. There is likely to be little chance of an accident causing the shutdown reactors of grounded aircraft to release radioactivity. However, the following questions should be asked:

- o Could a deliberate assault on a grounded nuclear aircraft with its reactor shutdown cause a release of radioactivity?
- o Based on the experience of the early civilian nuclear reactor program, is there a greater chance of releasing radioactivity during refueling than at other times? (Can moving the reactor vessel to specialized facilities significantly decrease this probability? What has been the Navy's experience with refueling nuclear submarines?)

Consequences. In addition to questions of crew and public safety that will be addressed in the next subsection, an accident at an airbase might hinder normal base operations.

- o Since one must evacuate an area when there is a nuclear accident, what can be done if radioactivity is released at an airbase?

If it is possible to cause a release, cannot one imagine a well-placed shot disabling an entire base?

CRASH ISSUES

The AFIT study concludes that th^ overall probability of a release of radioactive material for a nuclear-powered aircraft is dominated by the probability of a crash [10]. The AFIT work emphasized ground-impact crashes, but mid-air impacts may also be important.

Mid-Air Incidents

Mid-air incidents include mid-air collisions and the aircraft being attacked. Rom and Finnegan estimate that an emergency shutdown would take something on the order of tens of seconds [128].[a] A mid-air collision would be likely to occur with no warning; the safety systems for isolating the reactor might thus be damaged before they could do their jobs. However, it seem reasonable to assume that future collision-avoidance systems will be able to lower the probability of such accidents.

For an attack on the aircraft, the warning time depends upon numerous factors. Obviously, how successfully the reactor can be shut down is a function of the type of attack.

Probability of Occurrence. For a mid-air collision, sufficient warning time to shut down and/or isolate the reactor is the issue. For an attack, the issues are:

- How much warning time can be expected before an aircraft is hit in an attack?
- Would there be a trade-off between an evasive-maneuvering capability and implementing shutdown procedures for the reactor? (If there were no way to avoid being destroyed, the aircraft would isolate the reactor by closing the valves of the containment vessel; since this would be irreversible, the procedure would be undesirable if the airplane could possibly survive the attack.)
- Could a hit penetrate the containment vessel?

[a]However, clever design of the emergency shutdown system could reduce the time required substantially.

Even though the containment vessel is designed to withstand ground impact rather than possible penetration by a projectile, penetration of it appears to be unlikely. Since a nuclear-powered aircraft has one central heat source--the reactor--the engines are likely to be as close as possible to the reactor for efficiency reasons. Therefore, a heat-seeking device may come undesirably close to the section of the fuselage where the reactor is housed. Data on the battle experience of B-52s could be helpful in estimating the ability of large aircraft to sustain battle damage. However, the different configuration of a nuclear aircraft might prove more hazardous to the reactor than would be indicated by the B-52 data.

Consequences. The release of radioactivity in an air battle raises a different set of issues than a release in peacetime.

- Can the ability to evacuate an area affected by a radioactive release from a disabled nuclear aircraft be assumed?
- What are the potential costs if a defense line had to be evacuated?
- What would be the costs if there were no evacuation? (Since some of the effects triggered by radioactivity do not disable persons immediately, it is conceivable that forces would be left in place and be exposed to large doses of radiation.)

Obviously, hostile forces could be exposed to radiation as easily as friendly forces. This might lead to the conclusion that nuclear-powered aircraft would not be attacked if radioactivity might reach the enemy. As mentioned earlier, however, it may be unwise to assume such rational behavior.

Ground-Impact Incidents

The AFIT study presents the most comprehensive discussion presently available of the chance of a nuclear aircraft crash. Using attrition

data on bombers and cargo airplanes from the USAF Accident Bulletins for 1961 through 1973, a normal distribution with a mean of 1.46×10^{-5} per flight and a standard deviation of 0.348×10^{-5} was found. With this data, the nuclear aircraft's crash probability distribution per flight (for a 330-hour flight) was derived. Its mean is 4.83×10^{-3} with a 90 percent confidence interval of 3.07×10^{-3} to 6.55×10^{-3} [10].

Probability of Occurrence. In a crash of a nuclear-powered aircraft, the event that can generate costs unique to a nuclear aircraft is a release of radioactivity. The AFIT study describes the probability of this event as dominated by three factors: (1) the probability of the containment vessel's failing to withstand the afterheat transient, (2) the probability of the containment vessel's failing to withstand the impact, and (3) the probability of the failure of the containment vessel's isolation system at or before impact [10]

The probability estimates of these factors were calculated with a fault tree analysis based on the safety features assumed for the aircraft. As the AFIT study points out, the precise determination of such probabilities is impossible since some of the safety devices (such as the safety valves) do not exist.

- o Given the lack of data on the safety system's components, how much confidence should be placed in the range of probabilities used by the AFIT study?

At best, the data used by the AFIT study include crashes caused by hostile action as a subset of all crash statistics.

- o What is the conditional probability of the safety system's failure given that the aircraft is attacked?

Consequences. In a worst case analysis, Rom and Finnegan estimate that the general population within an area of 30,000 sq km downwind of the crash could receive a dose greater than the 10 rem allowed

by the Federal Radiation Council. Under average weather conditions, the area receiving radiation would be 12,000 sq km (4600 sq mi) [128].

Obviously, the consequences of a ground-impact and radioactivity release are strongly dependent on population density near the crash. Rom and Finnegan view the potential consequences of a release in a populated area as so great that they feel that nuclear airplanes will not be allowed to fly over populated areas unless "it can be demonstrated that virtually no fission products will escape from the reactor in the most serious crash situation" [128].

The AFIT study develops a crash probability distribution for the entire United States, assuming no flight over areas with densities greater than 10,000 people per square mile. Furthermore, a health effects model was combined with a dispersion model and the population model to derive a figure for the average number of deaths per accident; the figure was 18.9 [10]. The study asserts, with 99.5 percent confidence, that fewer than 865 fatalities could be expected from a radioactive release following a crash (for a 574-MWt reactor). The study then estimates that using worst-case assumptions in its estimates of core meltdown time, evacuation time, and the upper limit on fatal whole-body dose, an individual's risk of death from a nuclear aircraft is slightly greater than his risk of being killed by a meteor [10].

The risks are underestimated in the AFIT study, because it considers only deaths that take place within 30 days of the release and only immediate releases of radioactivity. Using only the early fatalities to measure consequences produces a serious underestimation. WASH-1400 uses BEIR[a] estimates of the magnitude of late somatic effects--cancers induced years or decades after the radiation exposure--at 50 to 165 deaths per million man-rem, respectively [136].[b]

There is an element of conservatism in terms of the risks to the U.S. population because the AFIT study assumes that all accidents occur

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[a]Committee on the Biological Effects of Ionizing Radiations of the National Academy of Sciences-National Research Council.

[b]These effects could be interpreted as radiological pollution effects rather than the "safety" (immediate) consequences addressed by the AFIT study.

in the conterminous United States. This assumption tends to overestimate the expected consequences; the consequences of a radioactive release following a crash at sea are apparently much less severe. Rom and Finnegan estimate the following results for a release of all fission products from a 250-MWt reactor operated for 1000 hours before impact into the sea:

> Submersion is no concern after one day (i.e., a person could swim in the water directly in the spot where the reactor impacted after one day). There would be some local seafood contamination that would cause some economic loss in a localized region for less than two months. In such an accident, only noble (inert) fission gases escape to the atmosphere. All other fission products condense or dissolve in the water, causing the contaminations just mentioned. The airborne dose from the noble (inert) fission gases that would be released would be less than the allowable dose at a distance 5 mi downwind from the impact point [128].

Questions related to the consequences of an impact release still remain:

- What are the full consequences that can be expected from a release of fission products on land?
- Does the estimate of the results of impact on water include possible concentrations of radioactivity in the food chain?

OBSTACLES TO UTILIZATION

Whatever the actual risks, there is a fear of nuclear energy that exceeds the magnitude of effects encountered so far from any peaceful use of nuclear power. This fear translates itself into political opposition to the use of nuclear power. Sometimes this opposition is to all uses of nuclear power, at other times to military uses or to uses near communities (i.e., "not in my neighborhood"). Opposition of this sort exists both domestically and internationally.

Internationally, the negotiations and agreements undertaken to obtain the right of nuclear submarines to enter foreign ports should

contribute to an understanding of the problems likely to be encountered when overflight and landing privileges are sought for nuclear-powered aircraft.

In considering the use of nuclear-powered aircraft, it is important to remember the possible impact of a serious nuclear accident on a nuclear weapon system's capability to function. Any serious nuclear accident, whether in the United States or elsewhere, whether related to a nuclear-powered aircraft, a nuclear central power station, or another source, can be expected to create strong pressure to ground all nuclear-powered aircraft.

OPTIONS FOR ADDRESSING THE DANGERS ASSOCIATED WITH NUCLEAR-POWERED AIRPLANES

If a fleet of nuclear-powered airplanes were desired because of their unique mission capabilities, the following options should be considered:

1. Shutdown of reactors over land at all times.
2. Shutdown of reactors over and approaching land.
3. Shutdown of reactors over land except during emergencies.
4. Flying of aircraft without reactor except during emergencies and over-water training exercises.
5. Limiting the hours of reactor operation before flying over land.
6. Developing amphibious aircraft or pure seaplanes as nuclear aircraft.
7. Utilizing special airfields located at sea.

The first three options are aimed at decreasing the danger of a radioactive release if there is a crash on land. Adapting the Way-Wigner formula, a statistical rule-of-thumb expression for the energy from fission products [131], the AFIT study derives a formula to estimate the radioactivity as a function of time after reactor shutdown,

$$A = A_0 t^{-0.2}$$

where A_0 is the radioactivity at shutdown, and t is time since shutdown (seconds). This approximation is useful for the 24 hours after shutdown [10]. Using this approximation, the radioactivity should decrease to less than 20 percent of its initial value one hour after shutdown. Therefore, reactor shutdown appears to be a useful way to decrease the possible consequences of a failure of the system containing the fission products.

Option 4 would eliminate the danger of nuclear accidents during routine operations. It might be particularly attractive if the grounded reactors could be used for other purposes. Option 5 might limit the ability of nuclear-powered aircraft to perform the missions for which they are uniquely qualified. Options 6 and 7 would decrease the dangers of takeoffs and landings, but might limit the areas which could be served by nuclear cargo airplanes.

RECOMMENDATIONS FOR RESEARCH

The literature on the safety of nuclear aircraft includes many hypothetical estimates and many fairly arbitrary standards. Before proceeding with the development of nuclear-powered aircraft, research is required to increase confidence in these estimates and standards. Muehlbauer presents the following tasks for the technological research on safety [25]:

- Develop and demonstrate containment vessel design method
- Design and demonstrate emergency valves for containment vessel penetrant lines
- Demonstrate proposed safeguards to prevent accident criticality
- Complete analysis of accidents involving soil burial of reactors

Mills recommends research on core meltdown and containment vessel integrity from impact and meltdown [111]. Until these tasks have been completed, it is difficult to view the failure-probability estimates as anything more than educated guesses; planning, therefore, should be based on operating such aircraft in such a way as to minimize the worst possible consequences (according to criteria not yet developed) of an accident.

In addition to the investigation of technological problems, research is needed on the political issues associated with nuclear aircraft. The difficulties encountered with nuclear submarines and the ways that these difficulties were overcome should provide some guidance on problems that might be met in connection with a nuclear airplane fleet. How civilian nuclear power within the United States progresses should provide some indication of domestic attitudes towards nuclear aircraft.

Before a decision to develop nuclear-powered aircraft is made, therefore, major technological and political research is required. Such a research program must determine:

1. The technical feasibility of the containment of radioactivity in the event of an accident,
2. The safest reactor type for airborne use, and
3. The political feasibility of such aircraft.

REFERENCES

1. Comptroller General of the United States, *Airlift Operations of the Military Airlift Command During the 1973 Middle East War*, General Accounting Office Report to the Congress, LCD-75-204, April 1975.

2. Scarbrough, D. R., and J. R. Peele, *Evaluation of the Stretched C-141A*, Lockheed-Georgia Co., LG74ER0052, April 1974.

3. Department of the Air Force, *Airlift Planning Factors*, AF Regulation 76-2, 11 April 1975.

4. *C-5B Tanker/Cargo*, Lockheed-Georgia Co., MER 582, June 1974.

5. Komer, R. W., et al., *Rationalizing NATO's Defense Posture* (U), The Rand Corporation, R-1657-ARPA/ISA/PA&E, March 1975 (Secret).

6. *Department of Defense Appropriations for 1975*, Hearings before the Subcommittee on the Department of Defense, House Appropriations Committee, February 26, 1974, p. 339.

7. Othling, W. L., et al., *Air Mobile Missile System Study (Conventional Aircraft)*, Aeronautical Systems Division, ASD/XR 74-1, February 1974.

8. Lau, J., et al., *Analysis of Remotely Manned Systems for Attacking SAM Sites* (U), The Rand Corporation, R-710-PR, September 1971 (Secret).

9. Lau, J., *Remotely Manned Systems for Tactical Air Operations: A Briefing* (U), The Rand Corporation, R-1111-PR, November 1972 (Confidential).

10. Amos, M. W., et al., *Nuclear Aircraft Feasibility Study*, Vol. 1, *Final Report*, Air Force Institute of Technology, GSE/SE-75-1, March 1975.

11. Federal Energy Administration, *Project Independence Report*, November 1974.

12. Department of Defense, *Management of Defense Energy Resources*, Phase II Report, 22 July 1974.

13. Department of Defense, *Standard Prices of Bulk Petroleum Items*, Defense Fuel Supply Center, July 1973 through July 1975.

14. Energy Research and Development Administration, *A National Plan for Energy Research, Development, and Demonstration*, ERDA-48, June 1975.

15. Office of Management and Budget, *Recommendations for a Synthetic Fuels Commercialization Program*, report submitted by Synfuels Interagency Task Force to the President's Energy Resources Council, June 1975.

16. Naill, R. F., D. L. Meadows, and J. Stanley-Miller, "The Transition to Coal," *Technology Review*, Vol. 78, No. 1, October 1975, pp. 19-29.

17. Mills, R. G., "Problems and Promises of Controlled Fusion Power," *Mechanical Engineering*, Vol. 97, No. 9, September 1975, pp. 20-25.

18. Williams, J. R., *Solar Energy--Technology and Applications*, Ann Arbor Science Publishers, Ann Arbor, Mich., 1974.

19. Gebman, J. R., and W. L. Stanley, with J. P. Weyant and W. T. Mikolowsky, *The Potential Role of Technological Modifications and Alternative Fuels in Alleviating Air Force Energy Problems*, The Rand Corporation, R-1829-PR, December 1976.

20. Yarymovych, M. I., *Final Report of the Air Force Energy R&D Steering Group*, Headquarters United States Air Force, Chief Scientist's Office, 15 November 1974.

21. Brewer, G. D., et al., *Summary Report: Study of the Application of Hydrogen Fuel to Long-Range Subsonic Transport Aircraft*, Lockheed-California Co., NASA CR-132558, January 1975.

22. *New Horizons II*, Vol. 1, *Executive Summary* (U), Headquarters United States Air Force, June 1975 (Secret).

23. Cleveland, F. A., "Size Effects in Conventional Aircraft Design," *AIAA Journal of Aircraft*, Vol. 7, No. 6, November 1970, pp. 483-512.

24. Coleman, H. J., "Tri-Mission C-5A Seen Saving $1.5 Billion," *Aviation Week and Space Technology*, Vol. 103, No. 11, September 15, 1975, pp. 24-25.

25. Muehlbauer, J. C., *Nuclear Power for Aircraft*, Lockheed-Georgia Co., LG74ER0068, May 1974.

26. Department of the Army, *U.S. Army Fact Sheet--Armor*, U.S. Army Command Information Unit, No. 12, March 1972, and No. 13, June 1972.

27. Weingarten, J. L., *Impact of Intermodal Containerization on USAF Cargo Airlift*, Air Force Systems Command, ASD-TR-72-76, August 1972.

28. Department of the Army, *U.S. Army Fact Sheet--Bridging Equipment*, U.S. Army Command Information Unit, No. 1, August 1971.

29. *Large Military Transport Aircraft Study*, Douglas Aircraft Company, PR-4-MA-4767, September 1974.

30. *Boeing 747F General Description*, The Boeing Commercial Airplane Company, D6-13920-R3, July 1974.

31. *Fuel Conservation Possibilities for Terminal Area Compatible Aircraft*, The Boeing Commercial Airplane Company, NASA CR-132608, May 1975.

32. Pinkel, B., A. Tenzer, and T. F. Kirkwood, *Mission Analysis of Aircraft Nuclear Propulsion* (U), The Rand Corporation, RM-5572-PR, March 1969 (Secret).

33. *The Tri-Mission Concept*, Lockheed-Georgia Co., October 1975.

34. *Military Applications of the Boeing 747*, Aeronautical and Information Systems Division, The Boeing Aerospace Company, D180-17655-1, December 1973.

35. Kulfan, R. M., and W. M. Howard, *Application of Advanced Aerodynamic Concepts to Large Subsonic Transport Airplanes*, The Boeing Commercial Airplane Company, AFFDL-TR-75-112, November 1975.

36. Synthetic Fuels Panel, *Hydrogen and Other Synthetic Fuels*, Division of Reactor Development and Technology (AEC), PB-224 482, September 1972.

37. Berkowitz, B., et al., *Alternative, Synthetically Fueled, Navy Systems: Force Element Missions and Technology*, General Electric Co.-TEMPO, Center for Advanced Studies, GE74TMP-46, November 1974.

38. Dyer, C. R., M. Z. Sincoff, and P. D. Cribbins (eds.), *The Energy Dilemma and Its Impact on Air Transportation*, 1973 Summer Faculty Fellowship Program in Engineering Systems Design, NASA Contract NGT 47-003-028, 1973.

39. *Handbook of Chemistry and Physics*, R. C. Weast (ed.), 53d ed., 1972-1973, CRC Press, Cleveland, Ohio.

40. Escher, W.J.D., *Prospects for Liquid Hydrogen Fueled Commercial Aircraft*, Escher Technology Associates, PR-37, September 1973.

41. Brewer, G. D., "The Case for Hydrogen-Fueled Transport Aircraft," *Astronautics & Aeronautics*, Vol. 12, No. 5, May 1974, pp. 40-51.

42. USAF Scientific Advisory Board, *Report of the Ad Hoc Committee on Future Air Force Energy Needs--Fuels and Systems*, November 1974.

43. Blocker, R. L., *C-5A System Effectiveness Report*, Directorate of Materiel Management, San Antonio Air Logistics Center, RCS: Log-MM(Q)7373, February 1975.

44. Reed, T. B., and R. M. Lerner, "Methanol: A Versatile Fuel for Immediate Use," *Science*, Vol. 182, No. 4119, December 1973, pp. 1299-1304.

45. Johnson, J. E., *The Economics of Liquid Hydrogen Supply for Air Transportation*, presented at the Cryogenic Engineering Conference, August 10, 1973, Atlanta, Ga.

46. Pangborn, J. B., and J. C. Shaver, *Analysis of Thermochemical Water-Splitting Cycles*, presented at The Hydrogen Economy Miami Energy (THEME) Conference, March 1974, Miami, Fla.

47. Farbman, G. H., and L. E. Brecher, *Process Applications of a Very High Temperature Nuclear Reactor (VHTR)*, Westinghouse Astronuclear Laboratory, presented at the 1975 IECEC.

48. Stanley, W. L., *Some Cost, Energy, Environmental, and Resource Implications of Synthetic Fuels Produced from Coal for Military Aircraft*, The Rand Corporation, P-5578, February 1976.

49. Rumsfeld, D. H., *Annual Defense Department Reports, FY 77*, Report of the Secretary of Defense to the Congress, January 1976.

50. Hill, P. G., and C. R. Peterson, *Mechanics and Thermodynamics of Propulsion*, Addison-Wesley Publishing Company, Reading, Mass., 1965.

51. Mow, C. C., and J. K. Ives, *Energy Consumption by Industries in Support of National Defense: An Energy Demand Model*, The Rand Corporation, R-1448-ARPA, August 1974.

52. Seamens, R. C., *A National Plan for Energy Research, Development, and Demonstration: Creating Energy Choices for the Future*, U.S. Energy Research and Development Administration, ERDA 76-1, April 1976.

53. Sharefkin, M., *The Fast Breeder Reactor Decision: An Analysis of Limits and the Limits of Analysis*, prepared for the use of the Joint Economic Committee, U.S. Congress, GPO 67-369, April 1976.

54. Rumsfeld, D. H., Department of Defense Directive No. 4140-43, December 5, 1975.

55. Hayes, J. H., *Future Army Deployment Requirements* (U), The Rand Corporation, R-1673-PR, April 1975 (Confidential).

56. Welch, J. A., Maj Gen, Hq USAF, Assistant Chief of Staff, Studies & Analysis, January 1976, private communication.

57. Research and Development Subcommittee of the Committee on Armed Services, *The Posture of Military Airlift*, U.S. House of Representatives, HASC No. 94-40, April 1976.

58. *Supply and Distribution of POL to Tactical Forces* (U), Institute for Defense Analyses, WSEG Report 204, June 1973 (Secret).

59. *International Petroleum Encyclopedia*, The Petroleum Publishing Co., Tulsa, Oklahoma, 1975.

60. Pinkel, I. I., *Future Fuels for Aviation*, AGARD Propulsion and Energetics Panel, NATO, July 1975.

61. Higgins, J. W., an unpublished Rand study of modeling airlift deployment, April 1975.

62. Sharpe, W. F., *The Army Deployment Simulator*, The Rand Corporation, RM-4219-ISA, March 1965.

63. *Feasibility of Hydrogen-Fueled Long Range Transports*, Vol. 1, *Summary Report*, McDonnell-Douglas Corporation, Report MDC J6295, May 1974.

64. Nicks, O. W., A. H. Whitehead, and W. J. Alford, *An Outlook for Cargo Aircraft of the Future*, NASA-Langley Research Center, NASA TM X-72796, November 1975.

65. Whitlow, D. H., and P. C. Whitener, *Technical and Economic Assessment of Span-Distributed Loading Cargo Aircraft Concepts*, The Boeing Company, NASA CR-144963, June 1976.

66. *Technical and Economic Assessment of Span-Loaded Cargo Aircraft Concepts*, Douglas Aircraft Company, Long Beach, Cal., NASA CR-144962, January 1976.

67. Johnston, W. M., et al., *Technical and Economic Assessment of Span-Distributed Loading Cargo Aircraft Concepts*, Lockheed-Georgia Co., NASA CR-145034, August 1976.

68. Fisher, G. H., *Cost Considerations in Systems Analysis*, The Rand Corporation, R-490-ASD, December 1970.

69. Kelley, J. H., and E. A. Laumann, *Hydrogen Tomorrow: Demands and Technology Requirements*, Jet Propulsion Laboratory, California Institute of Technology, December 1975.

70. Witcofski, R. D., "The Thermal Efficiency and Cost of Producing Hydrogen and Other Synthetic Aircraft Fuels from Coal," presented at the First World Hydrogen Energy Conference, Miami Beach, Fla., March 1976.

71. Tsaros, C. L., J. L. Arora, and K. B. Burnham, *A Study of the Conversion of Coal to Hydrogen, Methane, and Liquid Fuels for Aircraft*, Institute of Gas Technology, text of final oral presentation, Contract NAS1-13620, December 1975.

72. Kramer, J. J., et al., *Aircraft Fuel Conservation Technology*, Task Force Report, NASA Office of Aeronautics and Space Technology, September 1975.

73. Rohrback, C., and F. B. Metzger, *The Prop Fan--A New Look in Propulsors*, AIAA Paper No. 75-1208, presented at the AIAA/SAE Eleventh Propulsion Conference, Anaheim, Cal., September 1975.

74. Sturgeon, R. F., et al., *Study of the Application of Advanced Technologies to Laminar-Flow Control Systems for Subsonic Transports*, Lockheed-Georgia Co., NASA CR-144975, May 1976.

75. Hiebert, A. L., *Electromagnetic Implications of Advanced Composite Materials and Structures* (U), The Rand Corporation, R-1971-PR, May 1976 (Secret).

76. United Aircraft Research Laboratories, *Analysis of Nuclear Propulsion and Power-Conversion Systems for Large Subsonic Aircraft* (U), AFAPL-TR-72-47, September 1972 (Confidential).

77. United Aircraft Research Laboratories, *TFLCR/TFGCR User's Manual for Steady-State Performance of a Twin-Spool Turbofan with Chemical/Nuclear Capability. Customer Computer Decks*, L-971203-10, 31 March 1972.

78. Westinghouse Astronuclear Laboratory, *High-Temperature Liquid-Metal Cooled Reactor Technology*, WANL PR (HH) 006, July 1975.

79. Noggle, L. W., *Program Outline: Nuclear Aircraft Propulsion Technology*, ASD/XR, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, April 1974.

80. Roberts, R., *Report on Workshop on Light Weight Nuclear Power Plants*, Office of Naval Research, ONR-473-01-75, January 14, 1975.

81. Air Force Systems Command, *USAF Standard Aircraft/Missile Characteristics* (U), Air Force Guide Number Two, Vol. 1 (Green Book), November 1974 (Secret).

82. Cowart, W. L., *C-5B Tanker/Cargo Aircraft Feasibility Study*, Lockheed-Georgia Co., NMR74-1, April 1974.

83. Webb, J. A., *C-5 Advanced Tanker/Cargo Aircraft Configuration Description and Data*, Lockheed-Georgia Co., NMR75-5, March 1975.

84. Scarbrough, D. R., *C-5B and Austere C-5 Data Package*, Lockheed-Georgia Co., Operations Research Working Paper 74-9.1, June 1975.

85. Dommasch, D. O., S. S. Sherby, and T. F. Connolly, *Airplane Aerodynamics*, 3d ed., Pitman Publishing Corporation, New York, 1961.

86. Department of the Air Force, *Advanced Tanker/Cargo Aircraft (ATCA)* (U), Hq USAF Program Management Directive for Engineering Development, PMD No. R-Q 5-010-(1), July 1974 (Secret).

87. Comptroller General of the United States, *Corrections of Defects and Modifications--C-5A Aircraft*, U.S. General Accounting Office, Washington, D.C., December 1975.

88. Large, J. P., H. C. Campbell, and D. Cates, *Parametric Equations for Estimating Aircraft Airframe Costs*, The Rand Corporation, R-1693-PA&E, May 1975.

89. Nelson, J. R., and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974.

90. U.S. Air Force, *ASD Cost Research Report 110-A*, May 1973, revised May 1975.

91. Levenson, G. S., et al., *Cost-Estimating Relationships for Aircraft Airframes*, The Rand Corporation, R-761-PR (Abridged), February 1972.

92. Department of the Air Force, *U.S. Air Force Cost and Planning Factors*, AFM 173-10, April 1973.

93. Elliot, David M., and Lynn E. Weaver (eds.), *Education and Research in the Nuclear Fuel Cycle*, University of Oklahoma Press, Norman, Okla., 1972.

94. U.S. AEC, *Data on New Gaseous Diffusion Plants*, ORO-685, April 1972.

95. U.S. AEC, *Gaseous Diffusion Plant Operations*, ORO-684, January 1972.

96. U.S. ERDA, *Notes and Public Statements on Centrifuge Diffusion Plants*, Washington, D.C., 1974-1975.

97. U.S. ERDA, *Environmental Statement--Expansion of U.S. Uranium Enrichment Capacity*, Washington, D.C., June 1975.

98. *Competition in the Nuclear Power Supply Industry*, Arthur D. Little, Inc., NYO-3853-1, December 1968.

99. U.S. AEC, *The Generic Environmental Impact Statement on the Use of Recycled Plutonium in Mixed Oxide Fuel in LWR's (GESMO)*, Vol. 2, WASH-1327, August 1974.

100. Willrich, Mason, *Global Politics of Nuclear Energy*, Praeger Publishers, New York, 1971.

101. *Nuclear Engineering Handbook*, Harold Etherington (ed.), McGraw-Hill, Inc. New York, 1958.

102. Holdren, J., and P. Herrera, *Energy: A Crisis in Power*, Sierra Club, San Francisco, Cal., 1971.

103. U.S. AEC, *Energy Expenditures Associated with Electric Power Production by Nuclear and Fossil Fueled Power Plants*, WASH-1224-A, December 1974.

104. U.S. AEC, *Comparative Risk-Cost-Benefit Study of Alternate Sources of Electrical Energy*, WASH-1224, December 1974.

105. Noggle, L. W., memorandum on trip to Allied-Chemical Corp. and the Idaho Operations Office of ERDA, February 3, 1975.

106. Kennedy, K. K., H. K. Powell, and C. A. Hawley, Idaho Operations Office, ERDA, private discussions and memorandums, February 3, February 11, May 14, 1975.

107. U.S. AEC, "Uranium Hexafluoride: Base Charges, Use Charges, Special Charges, Table of Enrichment Services, Specifications, and Packaging," *38 Federal Register 4432*, February 14, 1973.

108. Baranowski, F. P., ERDA, Washington, D.C., private letter, December 11, 1974.

109. Staggs, J., ERDA, Washington, D.C., private discussion, July 22, 1975.

110. Devergie, P., ERDA, Washington, D.C., private discussion, July 22, 1975.

111. Mills, K. L., "Aircraft Nuclear Propulsion: A New Look in 1971," Ph.D. Dissertation, University of Virginia, June 1972.

112. Marcus, G. H., *Report of the AFRDQ Meeting on Nuclear Aircraft Propulsion Assessment, 18-20 February 1976*, ANSER Support Systems Division Note, SSDN76-9, July 1976.

113. Momenthy, A. M., "Fuel Subsystem Characteristics for LH_2 Aircraft," presented at the First World Hydrogen Energy Conference, Miami Beach, Fla., March 1976.

114. Snow, D. B., et al., *A Study of Subsonic Transport Aircraft Configurations Using Hydrogen (H_2) and Methane (CH_4) as Fuel*, NASA Langley Research Center and LTV, Inc., NASA, TM X-71994, August 1974.

115. Brewer, G. D., and R. E. Morris, *Study of LH_2 Fueled Subsonic Passenger Transport Aircraft*, Lockheed-California Co., NASA CR-144935, January 1976.

116. Mulready, R. C., "Liquid Hydrogen Engines," in Scott, Denton, and Daniels (eds.), *Technology and Uses of Liquid Hydrogen*, Pergamon Press, 1964.

117. Grobman, J., C. Norgren, and D. Anderson, *Turbojet Emissions, Hydrogen Versus JP*, NASA TM X-68258, May 1973.

118. Ruccia, F. E., et al., *Vulnerability of Airborne Cryogenic Fuel Tanks*, prepared by Arthur D. Little, Inc., for the Air Force Flight Dynamics Laboratory, August 1974.

119. Lippert, J. R., "Vulnerability of Advanced Fuel Systems for Aircraft," presented at the First World Hydrogen Energy Conference, Miami Beach, Fla., March 1976.

120. Schalit, L. M., and H. F. Read, *Military Applications of Liquid Hydrogen Fueled Aircraft*, Systems, Science, and Software, SSS-R-74-2345, July 1974.

121. Mangold, V. L., *Fragment Impact Protection of a Selected Double Wall LH_2 Fuel Tank Configuration*, Air Force Flight Dynamics Laboratory, AFFDL-TM-74-125-TPS, May 1974.

122. Bain, A. L., *Liquid Hydrogen Experience Applicable to Aircraft Operations, Kennedy Space Center*, NASA Kennedy Space Center, May 1973.

123. *Liquid Hydrogen Safety Manual*, prepared by Arthur D. Little, Inc., for USAF Air Research and Development Command, C-61092, October 1959.

124. Jaquette, D. L., *Possibilities and Probabilities in Assessment of the Hazards of the Importation of Liquefied Natural Gas*, The Rand Corporation, P-5411, April 1975.

125. Grobecker, A. S., S. C. Coroniti, and R. H. Cannon, *The Effects of Stratospheric Pollution by Aircraft*, U.S. Department of Transportation, Climatic Impact Assessment Program, DOT-TST-75-50, December 1974.

126. U.S. Environmental Protection Agency, *Compilation of Air Pollutant Emission Factors*, AP-42, 2d rev. ed., May 1974.

127. Mikolowsky, W. T., et al., *The Regional Impacts of Near-Term Transportation Alternatives: A Case Study of the Los Angeles Region*, The Rand Corporation, R-1524-SCAG, June 1974.

128. Rom, F. E., and P. Finnegan, "Will the Nuclear-Powered Aircraft Be Safe? *Astronautics and Aeronautics*, March 1968, pp. 32-40.

129. Grey, J., "Nuclear Aircraft Propulsion--Time for a Second Look," *New York Academy of Sciences Annals*, September 9, 1965, pp. 310-319.

130. Wild, J. M., "Nuclear Propulsion for Aircraft," *Astronautics and Aeronautics*, March 1968, pp. 24-30.

131. U.S. General Accounting Office, *Review of Manned Aircraft Nuclear Propulsion Program*, February 1963.

132. Rom, F. E., "Nuclear-Powered Airplane," *Technology Review*, December 1969, pp. 48-56.

133. Koenig, L. R., L. Randall, and C. M. Bhumralker, *On Possible Undesirable Effects of Heat Rejection from Large Electric Power Centers*, The Rand Corporation, R-1628-RC, December 1974.

134. Hottel, H. C., and J. B. Howard, *New Energy Technology*, Massachusetts Institute of Technology Press, Cambridge, Mass., 1971.

135. U.S. AEC, *Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants*, WASH-1400 (draft), August 1974.

136. Kendall, H. W., and S. Moglewer (eds.), *Preliminary Review of the AEC Reactor Safety Study*, Joint Review Committee, Sierra Club --Union of Concerned Scientists, San Francisco, Cal., November 1974.

GLOSSARY

ACL	Allowable cabin load
AFIT	Air Force Institute of Technology
AFSC	Air Force Systems Command
AGE	Aerospace ground equipment
ALCM	Air-launched cruise missile
ALMR	Airborne liquid-metal reactor
AMPR	Aircraft Manufacturer's Planning Report
AMST	Advanced medium STOL transport
APOD	Aerial port of debarkation
APOE	Aerial port of embarkation
ASD	Aeronautical Systems Division
ASW	Antisubmarine warfare
ATCA	Advanced tanker/cargo aircraft
AWACS	Airborne warning and control system
Btu	British thermal unit
C^3	Command, control, and communications
CER	Cost estimating relationship
CONUS	Continental United States
CRAF	Civil Reserve Air Fleet
DoD	Department of Defense
E.P.R.	Engine pressure ratio
ERDA	Energy Research and Development Administration
FH	Flying hours
HTGR	High-temperature gas reactor
ICBM	Intercontinental ballistic missile
IFR	In-flight refueling
IOC	Initial operational capability
ISI	Initial support increment
JP	Jet petroleum (JP is the military designation for conventional jet fuels currently derived from crude oil)

LCH_4	Liquid methane
LH_2	Liquid hydrogen
LMFBR	Liquid-metal fast breeder reactor
LOCA	Loss-of-coolant accident
LWR	Light-water reactor
MAC	Military Airlift Command
MMBtu	Million Btu
MQT	Model qualification test
MWe	Megawatts-electric
MWt	Megawatts-thermal
NRC	Nuclear Regulatory Commission
O&S	Operating and support
OPEC	Organization of Petroleum Exporting Countries
OR	Operational readiness
Quad	One quadrillion (i.e., 10^{15}) Btu
R&D	Research and development
RDT&E	Research, development, test, and evaluation
rem	Roentgen equivalent man
RPV	Remotely piloted vehicle
SAC	Strategic Air Command
SLS	Sea-level static
STOL	Short takeoff and landing
SWU	Separative work units
T.I.T.	Turbine inlet temperature
TOA	Time-of-arrival
TOGW	Takeoff gross weight
TSFC	Thrust specific fuel consumption
UE	Unit equipment
UTE	Utilization
VLA	Very large airplane